NBSIR 74-518

Instrumental Colorimetry of Retroreflective Sign Materials

I. Nimeroff, W. A. Hall

Optical Radiation Section
Heat Division
Institute for Basic Standards

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Prepared for
Federal Highway Administration
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U. S. DEPARTMENT OF COMMERCE, Frederick B. Dent, Secretary
NATIONAL BUREAU OF STANDARDS, Richard W. Roberts, Director

PREFACE

At the request of the Federal Highway Administration of the U.S. Department of Transportation, the National Bureau of Standards conducted a study to develop an instrumental procedure by which to specify and measure colors of retroreflective materials, as seen under nighttime illuminating and viewing conditions. The work included a study of the colorimetric properties of retroreflective materials used for highway signs and markings as evaluated under several conditions of illuminating and viewing geometry, particularly those that simulate nighttime use conditions. The opinions, findings, and conclusions in this report are those of the authors and are not necessarily those of the Federal Highway Administration. Certain commercially available equipment, instruments, or materials are identified in this report to specify adequately the experimental procedures used. In no case should such identification be inferred as recommendation or endorsement by the National Bureau of Standards, nor does the identification imply that the materials or equipment are necessarily the best available for the purpose.

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ABSTRACT

Because color-coded applications of highway signs increase, specifications of colors and color tolerances are required. In order to assure that the requirements are met within specified regions, a measurement technique needs to be developed and described. To accomplish these goals the U. S. Department of Transportation contracted with the National Bureau of Standards to conduct the required studies and make the necessary recommendations. Having previously performed a study for daytime conditions, the National Bureau of Standards was competent to perform a study for nighttime conditions. The colorimetric properties of 126 samples of retroreflective materials of 7 different colors were measured with 3 telecolorimeters in simulated nighttime conditions. One spectrophotometer was used to measure color of 38 of the samples in simulated daytime conditions. The colors measured were: red, orange, brown, yellow, green, blue and silver (white). Differences of color measured by means of different telecolorimeters on the same samples were evaluated.

As a result of these studies procedures for making colorimetric and photometric measurements were developed and are included in this report. On the basis of the color measurements and their variability tentative recommendations for color boundaries were prepared and are also included in this report.

INSTRUMENTAL

COLORIMETRY OF RETROREFLECTIVE SIGN MATERIALS

1. Introduction

Highway signs and demarcations are frequently marked with retroreflective materials. Theoretically, perfect retroreflecting materials reflect all of the unabsorbed light back along a direction that is opposite to that of the incident light. Consequently, any measurement of retroreflectively returned light should be measured along that direction. In general, however, retroreflective sheeting materials are not perfectly retroreflective, but reflect light in a distributive manner about the retroreflective direction. In the daytime they are observed by the driver under diffuse illumination and at night they are illuminated by the automobile's headlights and viewed by the driver seated behind the source.

For the Interstate Highway System seven colors are used for these materials: silver, blue, yellow, red, green, brown, and orange. The measurement of the color for compliance with the color and color tolerance of a particular batch of materials is done visually. For nighttime use that measurement and specification of the reflective properties of these materials be made at conditions of unidirectional illumination with varying entrance angle and small observation angle viewing. The entrance angle usually is less than 10° from the perpendicular to the sign at distances greater than 300 feet.

Federal Specification L-S-300A, dated January 7, 1970, for reflective sheeting and tape materials used for general purposes, on the other hand, states in paragraph 4.4.8 Color

> "Determine the color of the reflective material in accordance with ASTM-E-97-SS (Geometric characteristics must be confined to illumination incident within 10 deg. of, and centered about, a direction of 45 deg. from the perpendicular to the test surface; viewing is within 15 deg. of, and centered about, the perpendicular to the test surface. Conditions of illumination and observation must not be interchanged.) The standards for calibrating the test apparatus shall be the Munsell Papers designated in table I. They must be recently calibrated on a spectrophotometer. The test instrument shall be one of the following:
>
> 1. Gardner Multipurpose Reflectometer.
> 2. Gardner Model AC-2a Color Difference

3. Meeco Model V Colormaster.
4. Hunterlab D25 Color Difference Meter."

At the request of the Office of Traffic Operations through the Office of Research of the Federal Highway Administration, the Illuminating Engineering Group of the National Bureau of Standards was asked to conduct a research study of the color measurement and specification of retroreflective highway sign sheeting materials under nighttime conditions. The objective of this study was to develop an acceptable instrumental procedure to quantitatively measure the nighttime color by means of CIE tristimulus data of retroreflective sign sheeting materials representing the seven standard colors now in highway use.

A contract, dated December 20, 1972, Purchase Order No. 3-1-1011 and confirmed in March, 1973, states the various tasks required to achieve this objective:

1.1 <u>Statement of Work</u>

1.1.1 Collect a full representative range of samples of retroreflective highway sign sheeting materials that represent all current manufacturers and also represent a full variation in color range normally produced for each of the six (6) standard highway colors - blue, yellow, red, green, brown, and orange. Also include silver sheeting. Include all types of reflectorization that are in regular commercial production as well as 3M high intensity sheeting but specifically exclude other experimental materials.

1.1.2 As a reference, characterize the daytime-appearing color of each material by means of tristimulus data and chromaticity coordinates by instrumental means using a method developed in a previous contract (diffuse illumination and unidirectional viewing). Also include a reference visual comparison of each material to the color tolerance charts for daytime and nighttime appearing color.

1.1.3 Develop an instrumental procedure to measure the nighttime appearing retro-reflective color of the above materials. The method and instrument should be based on tristimulus color filters and CIE chromaticity coordinates and be capable of being easily obtained and utilized by State highway departments. The color properties of the light source in the method developed shall be equivalent to the average automobile headlight. Preliminary optical geometries to be studied shall include incidence angles of 2°, 25°, and 30°, and divergence angles of 0.2°, 0.5°, and 2.0°. From these the minimum and most appropriate geometries for a pertinent and standard measurement shall be evolved which are compatible with real headlight-sign-driver geometries. The method and instrumentation evolved shall be applicable for laboratory as well as field use.

1.1.4 Instruments to be utilized in item 3 above shall include as a minimum the Pritchard and Gamma photometers equipped with suitable color filters for tristimulus color evaluation.

1.1.5 The study leader shall make an on-site review at the 3M Company's technical center (J. Elstad) to determine the technical principles and procedures developed by them to address this particular problem of color measurement. Other companies such as American Decal and Manufacturing Co., Rohm and Haas, and the Munsell Co. shall be contacted and visited if necessary for additional input. Emphasis should be given to developing a suitable method based on the above-mentioned commercially available photometers or their commercial equivalents.

1.1.6 After 4 above, develop a proposed specification and limits for the color range permitted for nighttime-appearing retro-reflective color of reflectorized highway signs for the six (6) standard colors and silver based on tristimulus measurements and chromaticity coordinates.

1.1.7 As a supplement to the above work but in an exploratory and less exhaustive manner perform the work outlined in items 1 thru 6 on both raised reflectorized lane markers and reflectorized roadside delineators colored silver, red and amber. The types of reflectorization shall include corner cube, lens, beads or other. Raised traffic lane markers investigated shall include but not be limited to products from Stimsonite and Ray-o-Lite (corner cube) Borg-Warner (lens), Catadots (beaded), 3M (rods) and other types and manufacturers. Roadside reflectorized hazard markers shall be representative of all standard varieties from various sources. The range of incidence and divergence angles utilized shall approximate nighttime driver viewing geometrics (as seen from 40 to 400 foot distances from a moving vehicle).

1.1.8 Prepare and deliver monthly letter reports, a draft final report, and final report on the data and findings.

1.2 Partial Support by Federal Aviation Administration

Because of a common interest in the results of the study reported in this document, the Federal Aviation Administration supported this work in part.

2. Measurement System

2.1 Colorimeters and Standards

A photoelectric tristimulus colorimeter is a device that consists of a means for sampling three different parts of the visible spectrum and evaluating these by a system which correlates with human response to color. The system used most extensively is the CIE Standard Observer System, adopted by the International Commission on Illumination in 1931. It is possible to design optical filters that, together with a photodetector will closely approximate the three functions of the CIE System. To minimize the effect of the differences between the approximation and the actual function requires the use of standards with which to calibrate the instrumentation.

2.1.1 Standards can be of at least two different forms. One type of standard makes use of a white diffusing plate of known spectral reflectance and a series of reference filters that have spectral characteristics similar to those of the test materials. Figure 1 shows the spectral reflectance of a series of 4 reference filters, available from the National Bureau of Standards as standard samples: 2101 Red, 2102 Yellow, 2103 Green, and 2104 Blue, compared with the spectral reflectances of a series of typical retroreflective sheeting materials. The spectral characteristic red and yellow filters are similar to those of the red and yellow materials, while the spectral characteristics of the blue and green filters are sufficiently dissimilar to render their use impractical. To improve the accuracy of calibration other blue and green reference filters are required for this purpose.

As no single filter has the required spectral characteristics, a future investigation may attempt to design filter combinations that approximate the spectral reflectance characteristics of green and blue retroreflectors. The spectral curves shown in Figure 2, to approximate the curves shown in Figure 1 for green and blue retroreflective sheeting materials are based on nominal spectral transmittance data of combinations of the following Corning glasses:

Green: 4060 (2.0) + 4084 (4.5)
Blue: 3750 (5.0) + 3962 (2.5) + 5330 (3.4)

Numbers in parentheses are nominal filter thicknesses in millimeters.

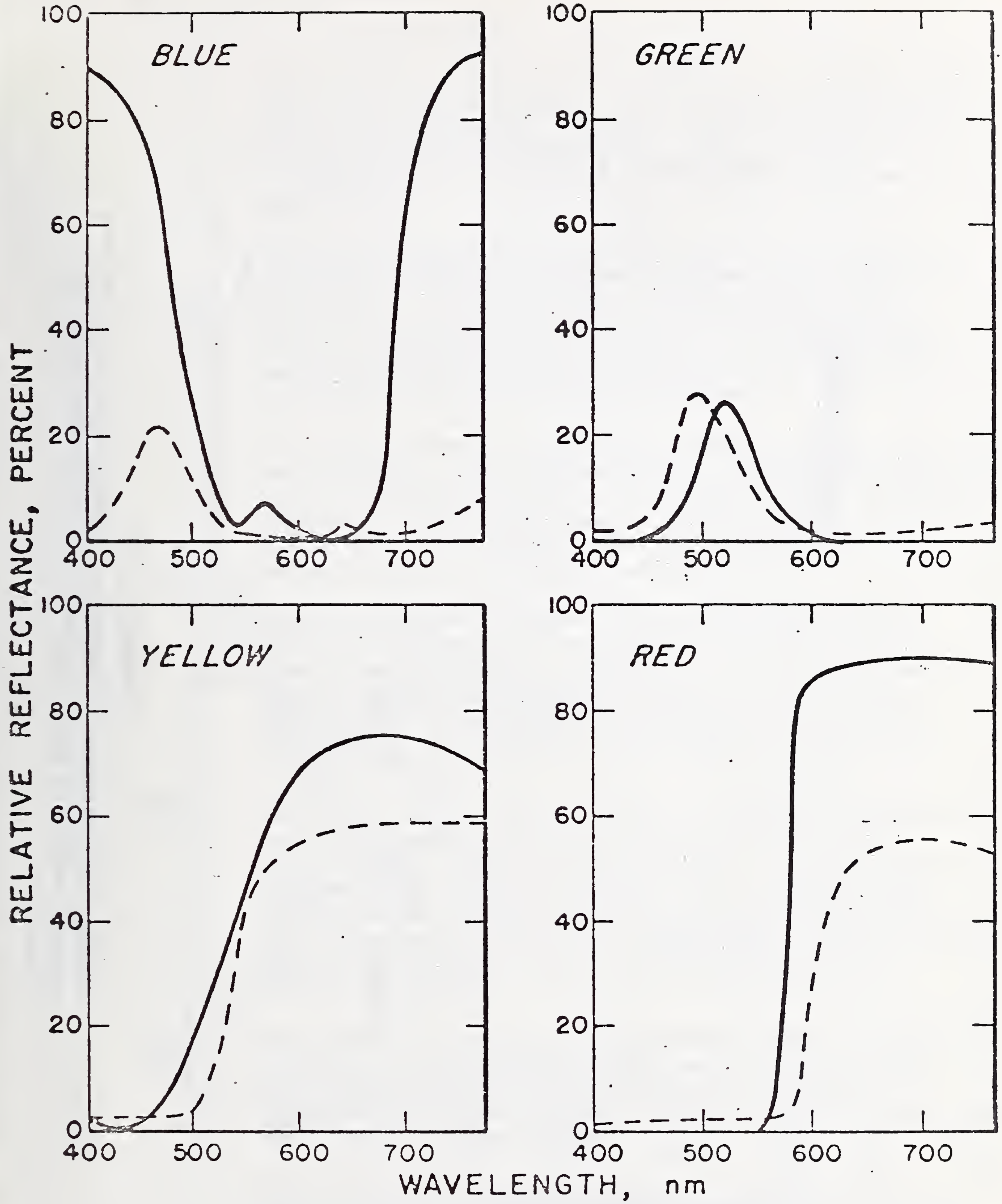


Figure 1. Spectral characteristics of reference filters (solid lines) compared with those of colored retroreflectors (dashed lines).

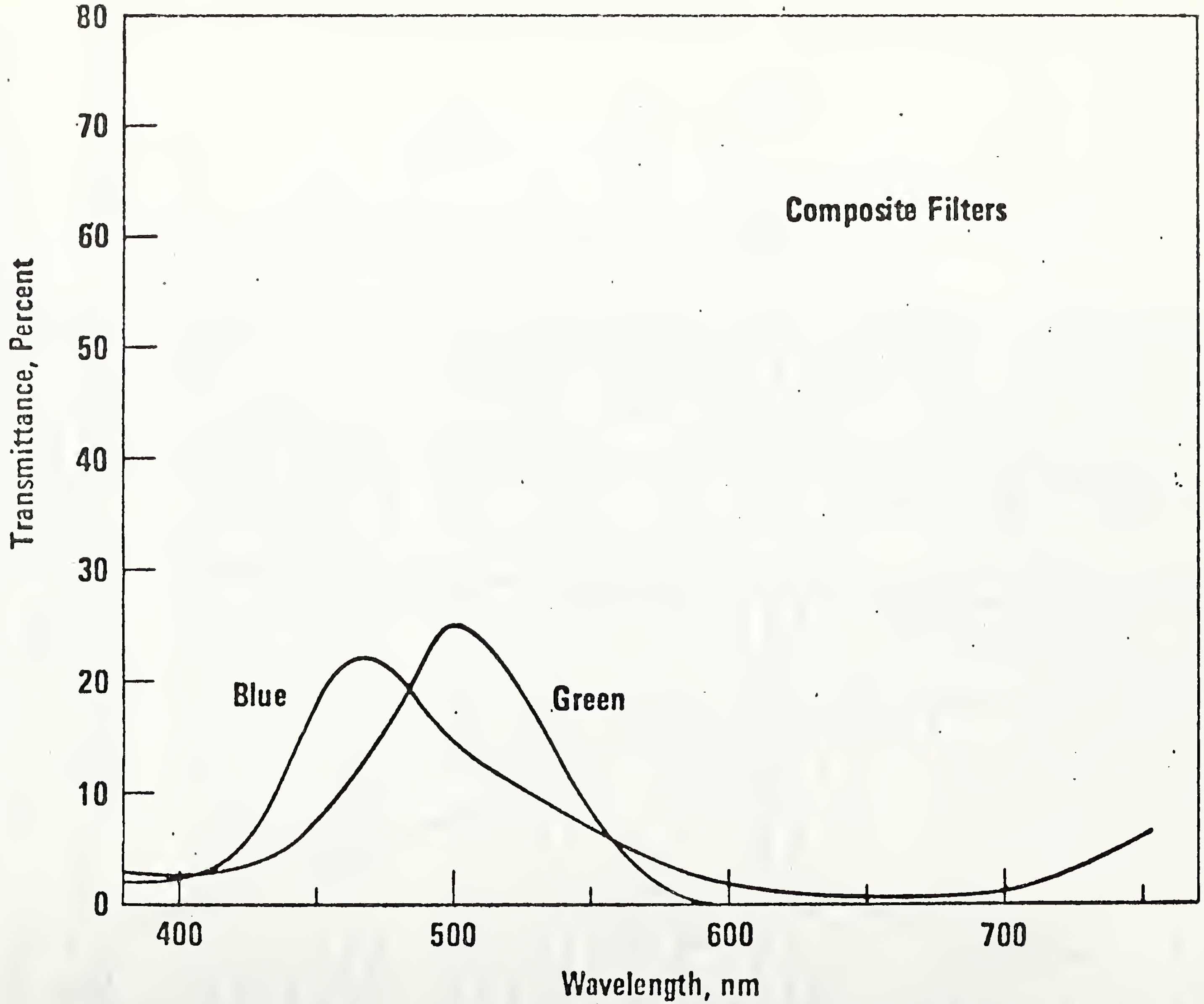


Figure 2. Spectral transmittance of reference filters suggested to improve spectral match for green and blue retroreflectors, shown in Figure 1.

The filters on hand were used as reference filters to calibrate our telecolorimeters. The spectral transmittances of the filters compared with the spectral reflectances of the retroreflective materials are shown in Figures 3 to 7 for white, red, yellow and orange, green, and blue, respectively.

A geometric arrangement for calibrating the instrument with white diffuser and filter is shown on the lower part of Figure 8. The angle of 45° is chosen because the spectral characteristics of the diffusers are generally known for this geometric condition. The entrance angle and observation angle for which the spectral reflectance of the diffuser is known should be used.

The reason for using a diffusing material in the calibration is to provide an illuminated area at a finite distance on which the telecolorimeter can be focussed and to minimize effects of slight misalignment. Misfocussing, a possible source of errors, should be avoided, minimized, or its effect evaluated and correction applied.

There are several materials that can be used as white diffuse reflectors of known spectral characteristics. These are: MgO, $MgCO_3$. and $BaSO_4$. The last one, $BaSO_4$, may be the most convenient to use because it is less fragile than MgO and whiter than $MgCO_3$. The diffuser should be of such size that the colorimeter looks at an illuminated area within the area of the diffuser.

The upper part of Figure 8 shows an alternate calibration method, employing a diffuse transmitting material of known spectral characteristics, such as a singly-flashed opal diffuser, also is available. This method was used in calibrating our colorimeters with which we made the color measurements reported in this paper. The measurement geometry of entrance angle and observation angle is shown in Figure 9.

Photoelectric tristimulus colorimeters, when properly calibrated can give reasonably stable and accurate results. The filters are quite good approximations to the CIE standard colorimetric observer functions and the electronics are quite stable and reliable.

What constitutes a proper calibration standard for a photoelectric tristimulus colorimeter? Ideally, when the test material is highly selective either in its spectral

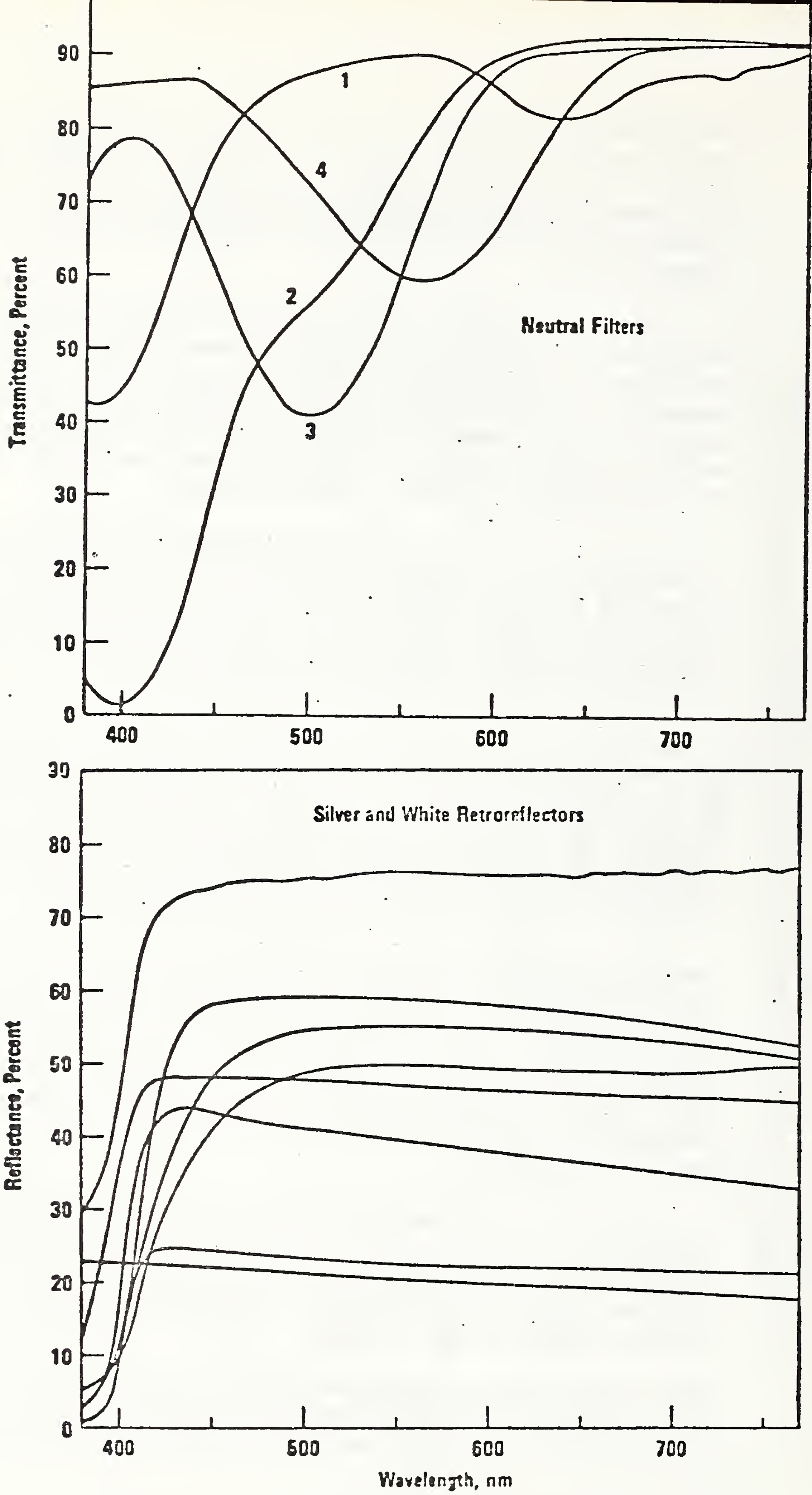
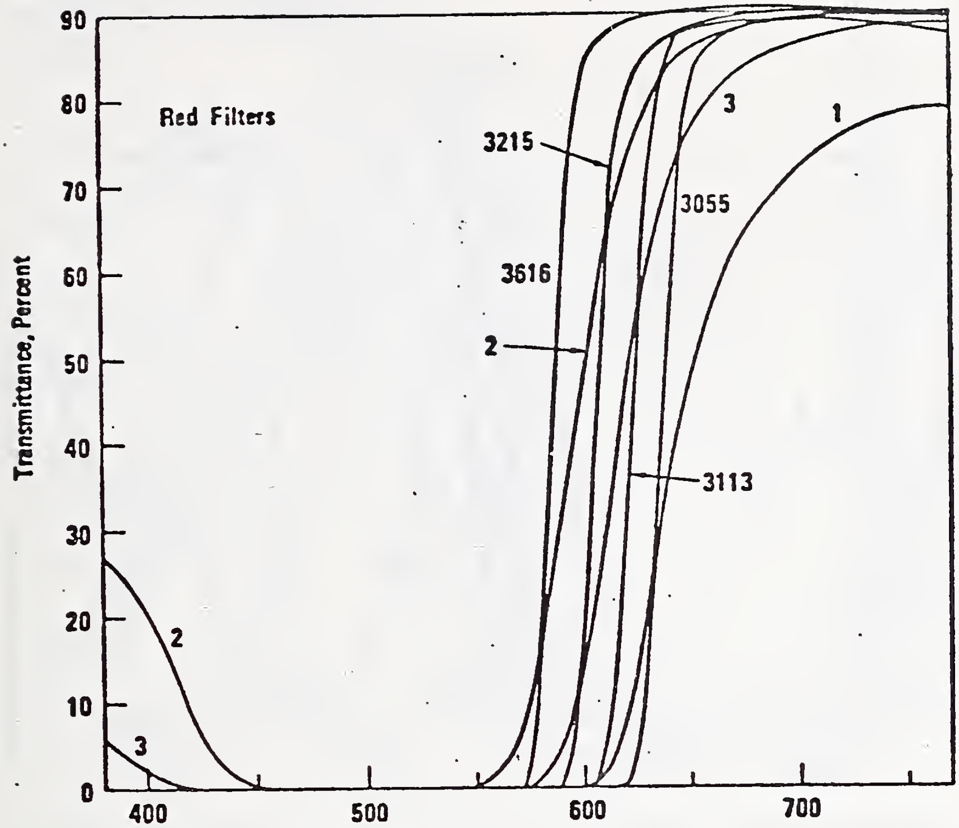


Figure 3. Filters used in this study as reference filters for white and silver retroreflectors.



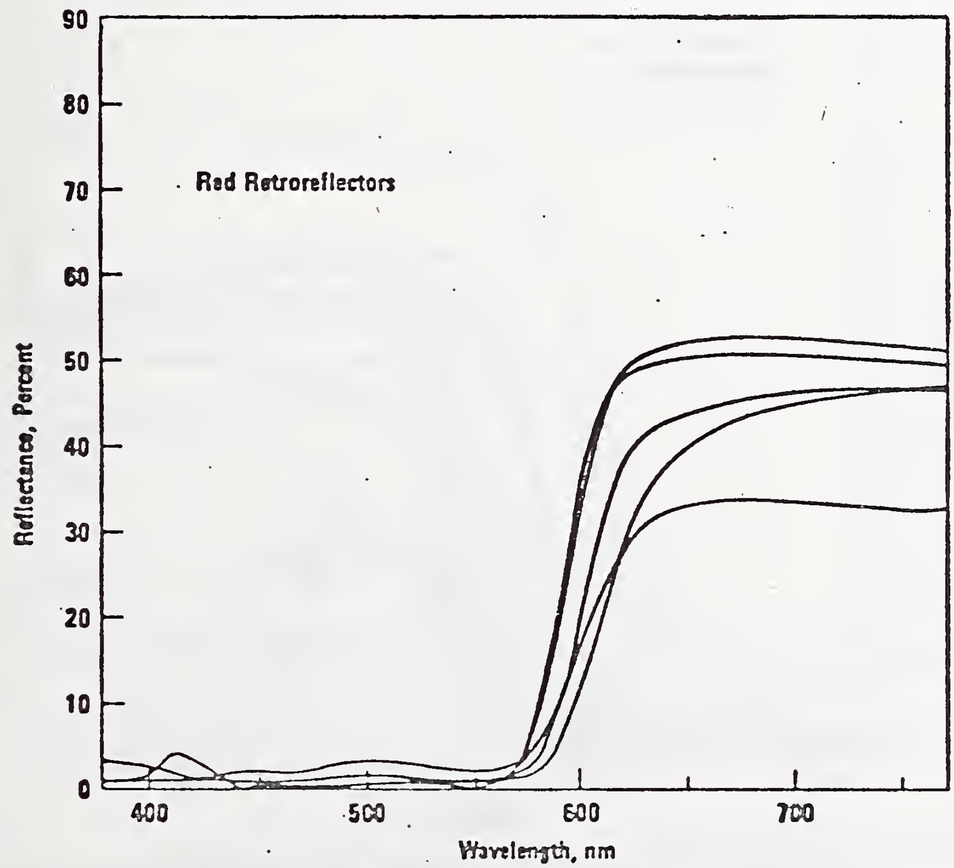


Figure 4. Filters used in this study as reference filters for red retroreflectors.

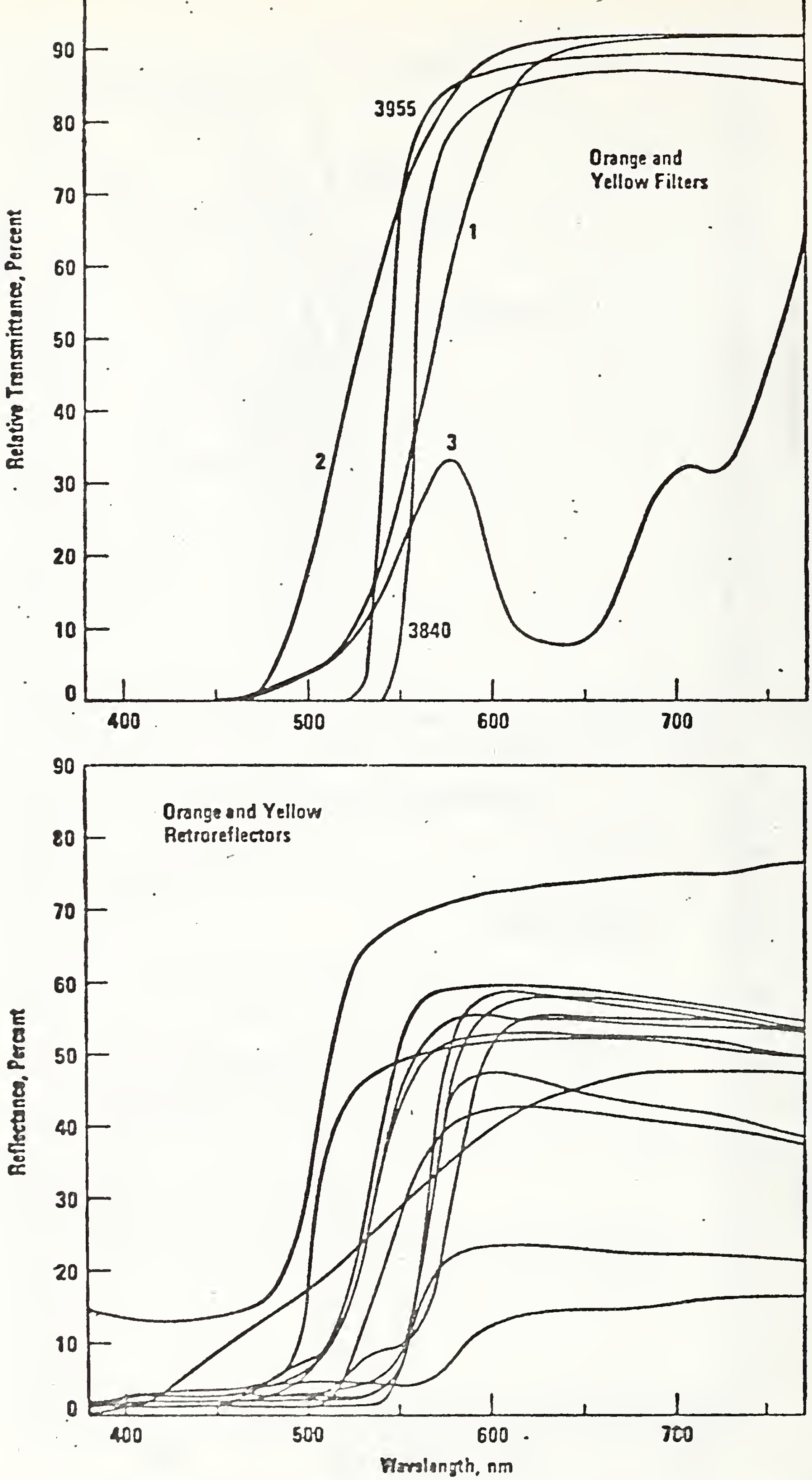


Figure 5. Filters used in this study as reference filters for yellow and orange retroreflectors.

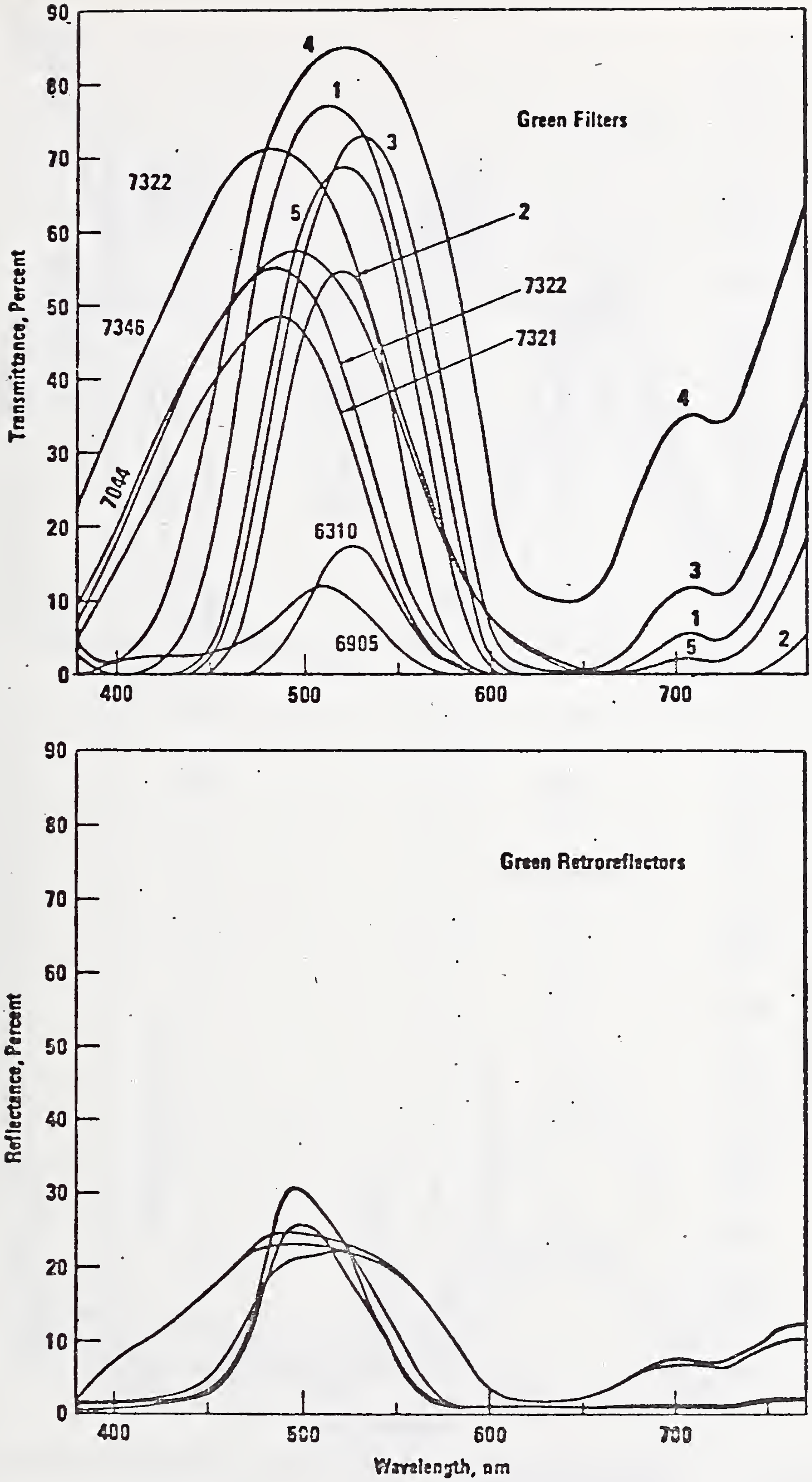


Figure 6. Filters used in this study as reference filters for green retroreflectors.

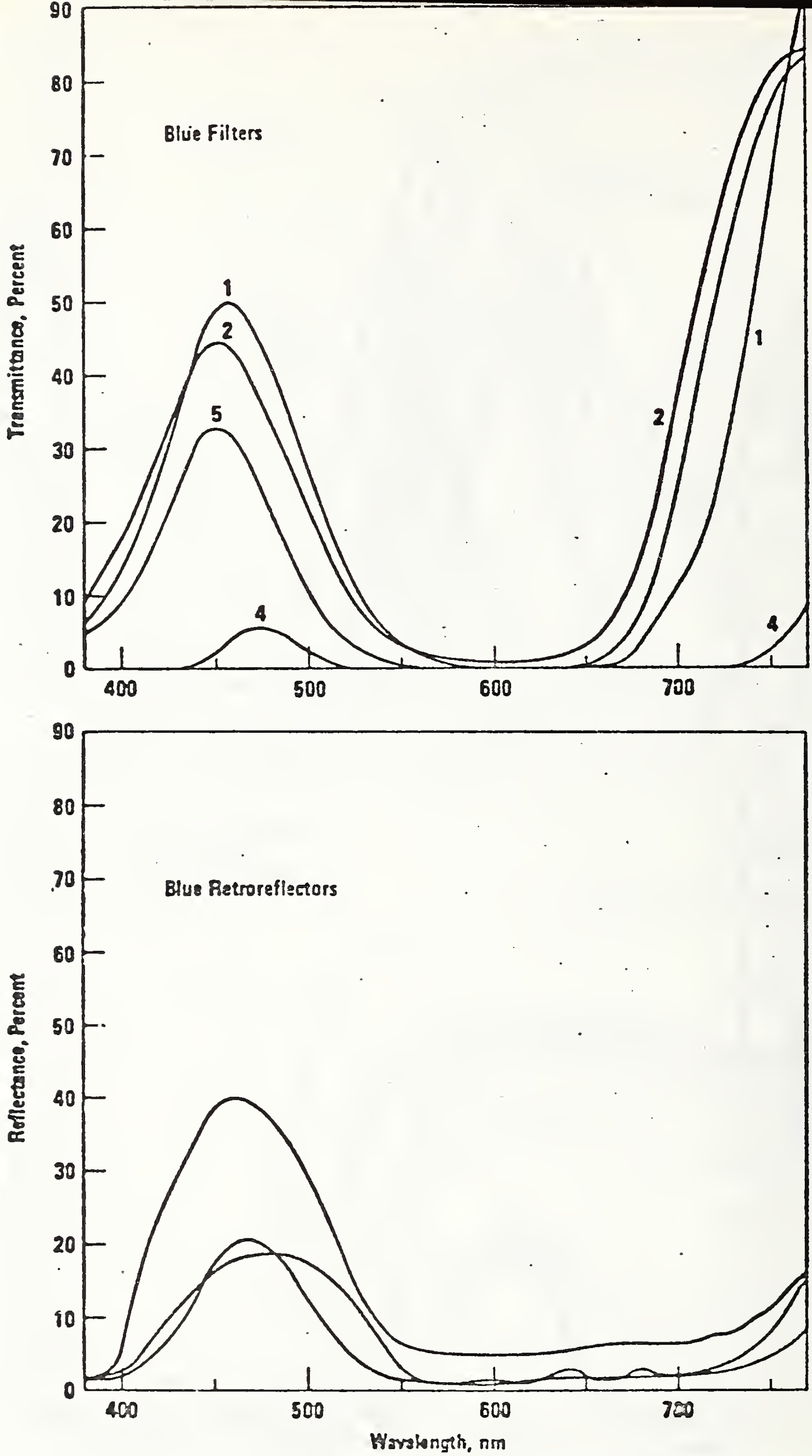


Figure 7. Filters used in this study as reference filters for blue retroreflectors.

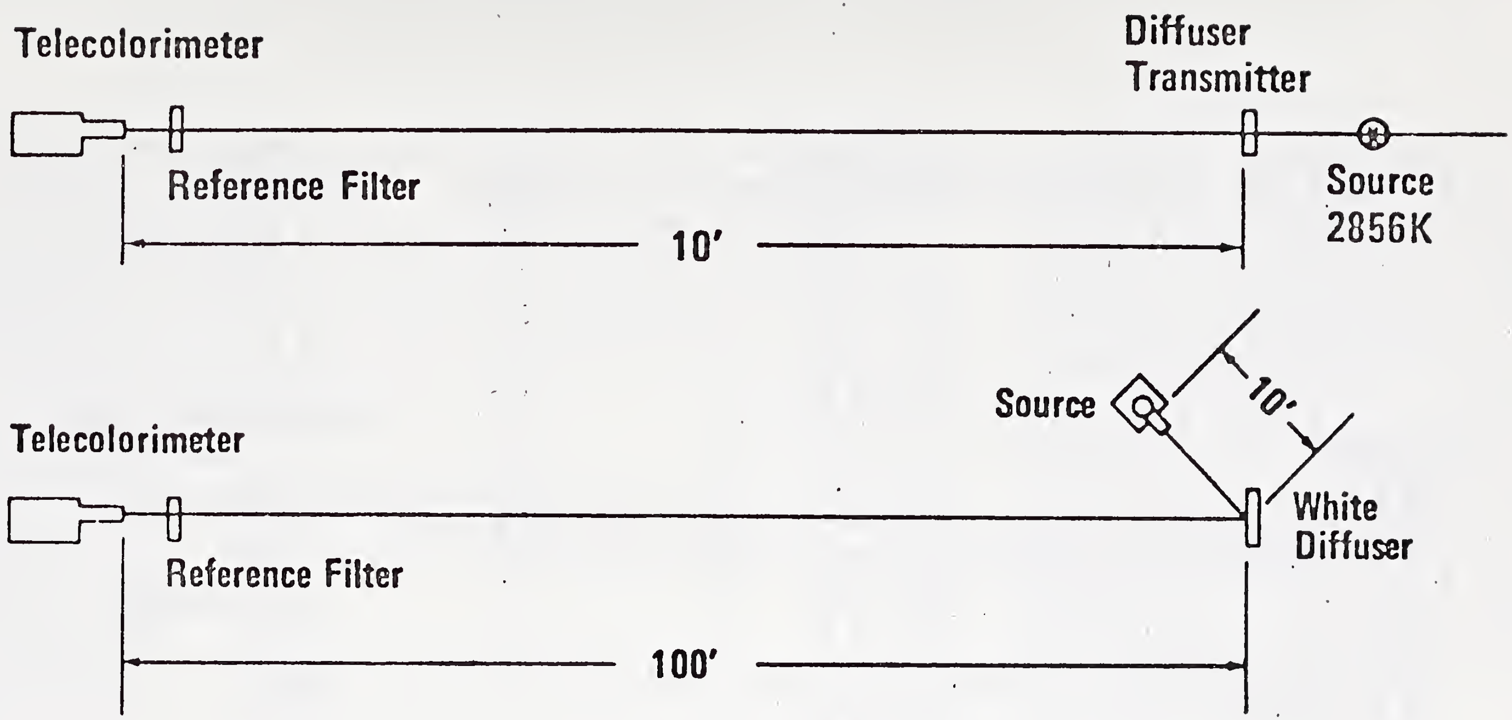


Figure 8. Alternate calibration geometries.

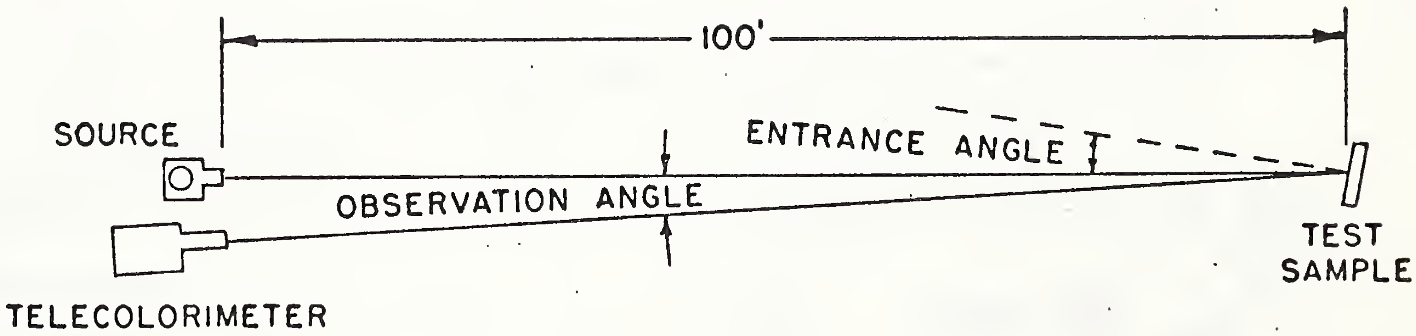


Figure 9. Measurement geometry for nighttime conditions.

or geometric reflectance properties, as retroreflectors are, then materials of essentially the same spectral and geometric characteristics as the test material should be used as standards with which to calibrate the instrument. Before such standards are used, however, care should be taken to assure that their assigned values are reasonably correct for the required geometric conditions. An effort is being made at NBS to develop such standards.

Once the instrument (telecolorimeter) is set to read the correct tristimulus values of the white diffuser then the proper reference filter is inserted in the light path and the tristimulus values are read. Correction factors are then derived as the ratio of the reading to the known values for the filter-diffuser combination.

With the components, source, test sample, and receptor in place, measurements can be made without further adjustments to the telecolorimeter. To obtain the correct tristimulus values X, Y, Z, the readings X', Y', Z' should be multiplied by the correction factors, F_X, F_Y, F_Z, obtained thus:

$$X = X' F_X = (X'_r + X'_b) F_X$$

$$Y = Y' F_Y$$

$$Z = Z' F_Z$$

From these correct tristimulus values the chromaticity coordinates can be computed.

$$x = X/ (X + Y + Z)$$

$$y = Y/ (X + Y + Z)$$

Average correction factors were derived and used to obtain tristimulus values from the telecolorimeter readings. Chromaticity coordinates were computed from these corrected tristimulus values.

2.1.2 The other type of standard makes use of actual retroreflective materials of which the spectral and geometric characteristics are similar to the test materials. This type of standard has the advantage over the use of glass filters in that the standards would have similar geometrical retroreflective characteristics as the test samples. This is important with materials that are as geometrically selective as retroreflectors. As is shown later in this report, the color appearance of retroreflective materials

depends on the geometrics of incidence and viewing.

2.2 Daytime Geometry

In daytime a highway sign is illuminated by skylight and viewed in a direction that is nearly perpendicular to the plane of the sign. If at all feasible, the color measurement geometry should simulate these geometric use conditions, that is, diffuse illumination with daylight spectral distribution and approximately perpendicular viewing. This geometry has been recommended in Report FHWA-RD-71-1 dated November, 1971. (This report is available from the National Technical Information Service, Springfield, Va. 22151, under Document Accession No. PB 204-586.)

2.3 Nighttime Geometry

At night a highway sign is illuminated by the automobile headlights operating at about 2856K. A schematic representation of the geometric situation is shown in Figure 10. The sign is illuminated along an incidence line different from the reference axis, the line perpendicular to the sign at its center. The angle between these two lines is the entrance angle. The light that is retroreflected by the sign is usually viewed at an angle slightly different from the incidence angle. The angle between the incidence line and the observation line is called the observation angle. These angles, entrance and observation, change dynamically as the observer approaches the sign. A general description of the geometry of retroreflectors in the nighttime illuminating and viewing situation is shown in Figure 11. Consequently, the geometry under which the photometric and colorimetric measurements are made should approximate the condition under which the sign is seen and read during the approach by the observer.

A relationship between the entrance angle ε_2, the observation angle α, the viewing angle ε_1 and the position angle γ may be established by application of geometric and trignometric principles. This relationship is:

$$\cos \alpha \cos \varepsilon_2 + \sin \alpha \sin \varepsilon_2 \cos \gamma = \cos \varepsilon_1$$

Several special cases readily can be used to test this relationship.

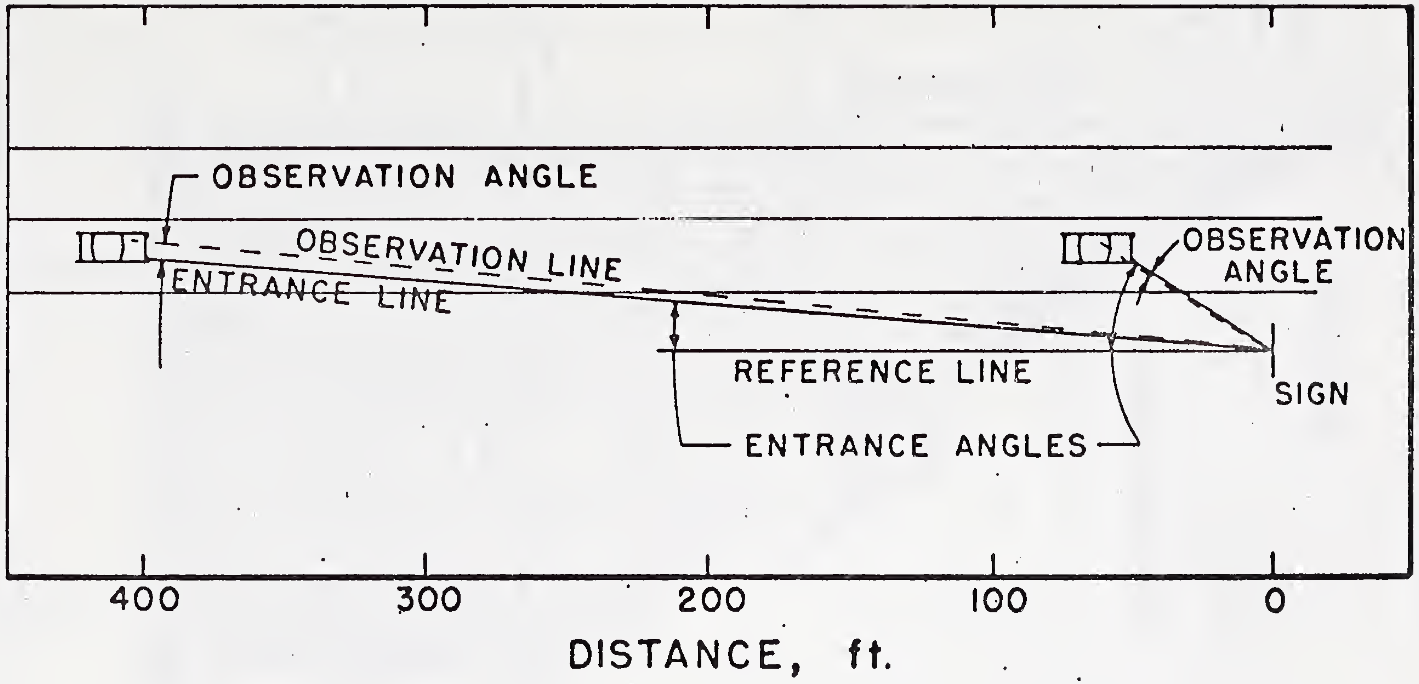


Figure 10. Schematic nighttime highway sign entrance and observation geometry.

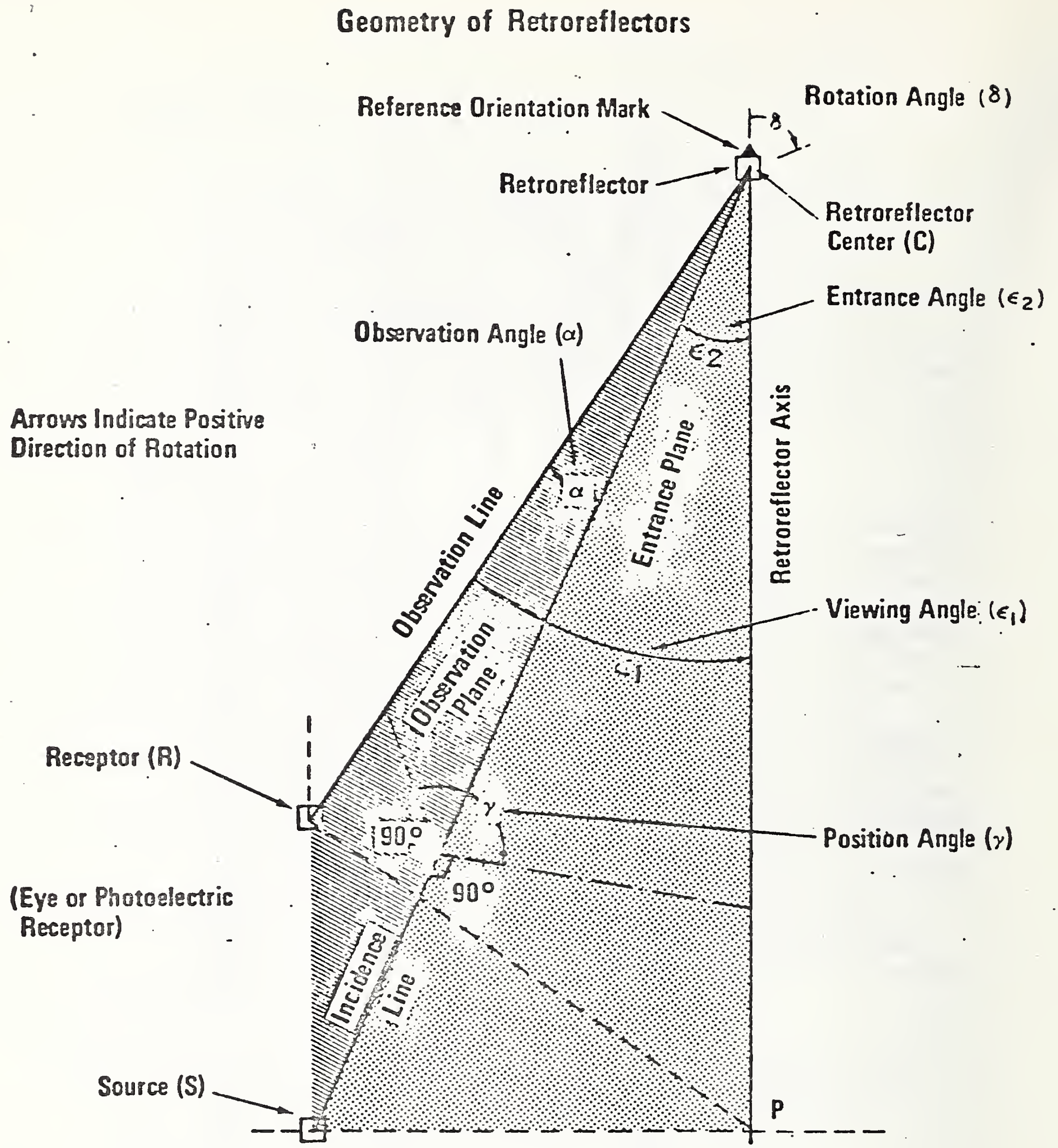


Figure 11. Geometry of retroreflectors, with lines, angles and planes defined

Conditions	Results
I. $\gamma = 0°, \cos\gamma = 1$	$\cos\alpha\cos\varepsilon_2 + \sin\alpha\sin\varepsilon_2 = \cos\varepsilon_1$
	$\cos(\alpha - \varepsilon_2) = \cos\varepsilon_1$
	$\alpha - \varepsilon_2 = \varepsilon_1$
II. $\gamma = 180°, \cos\gamma = -1$	$\cos\alpha\cos\varepsilon_2 - \sin\alpha\sin\varepsilon_2 = \cos\varepsilon_1$
	$\cos(\alpha + \varepsilon_2) = \cos\varepsilon_1$
	$\alpha + \varepsilon_2 = \varepsilon_1$
III. $\gamma = 90°, \cos\gamma = 0$	$\cos\alpha\cos\varepsilon_2 = \cos\varepsilon_1$
	$\cos^{-1}(\cos\alpha\cos\varepsilon_2) = \varepsilon_1$
IV. $\alpha = 0°, \cos\alpha + 1$	
$\sin\alpha = 0$	$\cos\varepsilon_2 = \cos\varepsilon_1$
	$\varepsilon_2 = \varepsilon_1$

The usual entrance angles for measurement of specific intensity or specific luminance are -4°, 15°, and 30°, and the usual observation angles, angles between the entrance and observation lines for these photometric measurements are usually 0.2°, 0.5°, and 2.0°. Recent discussions among retroreflector manufacturers and government laboratories have suggested that 0.2° observation be replaced by 0.33° and that 5° entrance angle be added. These angles are listed in Table I.

Table I. Entrance and Observation Angles

Entrance Angles	Observation Angles
- 4°	0.2°
5°	0.33°
15°	0.5°
30°	2.0°

2.4 Special Geometries

For some special purposes, such as highway delineator markers and highway lane stripes, geometries other than those described above are required. Since the painted highway lane stripes are placed on a horizontal plane, for example, the entrance angle would be rather large, close to 90° from the reference axis. Entrance angles used for this purpose are specified in Federal Specification TT-P-85D, Paint, Traffic, Reflectorized, for Airfield Runway Marking (drop-on-type), and are either 75° or 88°. Observation angle is specified in this document as 1° 20' for either entrance angle.

Because raised lane delineators are sloped relative to the road, the entrance angle is less than that for painted highway stripe.

3. Colorimetric Measurements

3.1 Materials Used

The materials used were those made by three manufacturers. These consisted of 32 retroreflective sheeting materials made by two manufacturers and 6 molded cube-corner retroreflectors made by a third manufacturer. Of the retroreflector sheeting materials made by one of the manufacturers two were the so-called "diamond grade" composed of diamond-shaped sections with very small, possibly embossed, corner-cube retroreflective elements, five were the so-called "high intensity" grade and had hexagon-shaped sections, and two were of glass-bead impregnated fabric.

The retroreflective materials with diamond-shaped sections have different retroreflecting characteristics for different orientations of the major and minor diagonals of the diamond sections. The hexagonal section dividers support the outer covering which encapsulates the retroreflective elements. The remaining 25 retroreflective sheeting materials were of the engineering grade. In Table II are listed the various retroreflective materials that were used in this study together with their trade numbers, nominal color, and other special descriptive remarks. All of these were used for the daytime color measurements. Some, however, were not used in the nighttime color measurements. The group of samples listed in Table II will be called the "NBS set" in this report.

Forty-four additional samples of retroreflecting sheeting, part of an international interlaboratory study, were supplied by their manufacturer. These were used to make photometric and colorimetric measurements under nighttime conditions. They were mounted on 1/16" aluminum plate, 6 inches square. This set of samples consisted of white, red, orange, yellow, green, and blue "engineering" and "high intensity" grade retroreflective sheeting. Table III shows the designated numbers, name, and grades of these samples of retroreflective sheeting. This group of samples will be called the "Interlaboratory Set" in this report.

3.1.1 Reason for Only One Brown Sample. In response to a request of manufacturers of retroreflective materials of "engineering" grade or better, only one manufacturer submitted a brown retroreflective sheeting sample. Apparently this is the only brown retroreflective sheeting available in the "engineering" grade or better.

Table II. The NBS Set of Materials Used in this Study

Manufacturer	Material	No.	Manufacturers' Color Name	Descriptive Remarks
3-M Co.	Retroreflective Sheeting	3070	Silver	"Engineering" Grade
"	"	FEA681	Blue	"
"	"	FEA675	Yellow	"
"	"	FEA588	Orange	"
"	"	FEA556	Silver	"
"	"	3279	Brown	"
"	"	3277	Green	"
"	"	3276	Blue, light	"
"	"	3275	Blue	"
"	"	3273	Yellow, weak	"
"	"	3272	Orange-red	"
"	"	3271	Yellow	"
"	"	3270	Silver	"
"	"	3285	Black	"
"	"	3284	Orange	"
"	"	3282	Red	"
"	"	3281	Yellow	"
"	"	3280	Silver	"
"	"	X3302	Red	"Diamond" Grade
"	"	X3300	Silver	"
"	"	3384	Orange	Hexagon ("High Intensity") Grade
"	"	3877	Green	"
"	"	3872	Red	"
"	"	3871	Yellow	"
"	"	3870	Silver	"
"	"	RF151	Yellow	Fabric, "Engineering Grade"
"	"	RF150	White	"

Table II. (Continued)

Manufacturer	Material	No.	Manufacturers' Color Name	Descriptive Remarks
American Decal & Mfg. Co.	Retroreflective Sheeting	-	Green	"Engineering Grade"
"	"	AD242C	Yellow	"
"	"	AD240E	Orange	"
"	"	AD238D	Red	"
"	"	AD229E	Silver	"
Amerace-Esna Corp.	Cube-corner Retroreflective Plaques	PMO-M/B	Green	Metalized, Rectangular 2.5" x 3", Molded Stimsonite
"	"	PMO-M	Green	Unmetalized, Rectangular, 2.5" x 6", Molded Stimsonite
"	"	2400	Crystal	Rectangular, 3" x 6", Molded Stimsonite
"	"	FOS-975	Crystal	Center Mount, 3" diameter, disk, Molded Stimsonite
"	"	#12A-R	Red	3" diameter, disk, Molded Stimsonite
"	"	#12A-A	Amber	3" diameter, disk, Molded Stimsonite

Table III. The Interlaboratory Set

No.	Color Name	Manufacturer	Grade
1	White	3M	"High Intensity"
2	"	"	H
3	"	"	"Engineering"
4	"	"	E
5	"	"	E
6	"	"	E
7	Yellow	"	H
8	"	"	H
9	"	"	E
10	"	"	E
11	"	"	E
12	"	"	E
13	Red	"	H
14	"	"	E
15	"	"	E
16	"	"	E
17	"	"	E
18	"	"	H
19	"	"	E
20	"	"	E
21	Blue	"	H
22	"	"	E
23	"	"	E
24	"	"	H
25	"	"	E
26	"	"	E
27	"	"	E
28	Green	"	H
29	"	"	H
30	"	"	E
31	"	"	E
32	"	"	E
33	"	"	H
34	"	"	E
35	"	"	E
36	Orange	"	H
37	"	"	H
38	"	"	E
39	"	"	E
40	"	"	E
41	"	"	E
42	"	"	H
43	"	"	E
44	"	"	E

A brown retroreflector is actually dark orange or, in some instances dark yellow or dark red, when seen in daylight. But when seen at night as a retroreflector, it appears as a dim source that may be mistaken for these other colors.

3.1.2 Reasons for Nonperformance of 1.1.7. A number of circumstances delayed the effective start of the measurement part of the study. Because of this, the large number of samples collected, the large amount of work required, and the low priority given in 1.1.7 of the work statement, measurements were not made on raised reflectorized lane markers and reflectorized roadside delineators. However, cube-corner retroreflective roadside delineators often have characteristics similar to those of the retroreflective plaques listed in Table II. The procedures developed and reported in Section 5, Recommended Test Procedure for Nighttime Conditions are also applicable to these materials.

3.1.3 Sample Sizes. The NBS set of retroreflective sheeting materials listed in Table II were supplied in 12-inch squares. From these, 2-inch squares were cut for the spectrophotometric measurements described below and 6-inch squares were cut for the colorimetric measurements with the telecolorimeter.

The molded plaque cube-corner retroreflectors were measured with the spectrophotometer and the telecolorimeters in the sizes supplied. The sizes of these retroreflective materials are shown in Table II.

3.2 Spectrophotometric Measurements for Daytime Color

The spectrophotometric measurements were made in terms of the spectral radiance factor.

Measurements of spectral radiance factor of the NBS Set of Materials (listed in Table II) were made by means of a Cary Model 14 recording spectrophotometer equipped with a Model 1411 integrating sphere type reflectance attachment, a linear slidewire (0 to 100%T), and a Hamamatsu R136 (near S-20 surface) multiplier phototube detector. The integrating sphere of the Model 1411 reflectance attachment was irradiated with non-dispersed flux from a tungsten source focused on the opening at the bottom of the integrating sphere. The specimen is irradiated hemispherically and that portion of the irradiating flux which is reflected in a direction 6° from the normal to the specimen surface is passed through the monochromator for analysis. This geometry is nominally diffuse illumination and perpendicular viewing and may be represented

as D/O. Strictly speaking however, it is D/6. The spectral band-pass was approximately 1 to 2nm. The width of the slits of the monochromator is automatically adjusted throughout the spectral scan in order to maintain a constant energy signal as sensed by the electronics during the reference beam cycle.

The photometric scale of the instrument was set to record 100% by means of the identical MgO references located at the sample and reference openings of the integrating sphere. The spectral radiance factor of a reflectance standard (white-glass standard TW1-B1) was measured together with the specimens in order to obtain data with which to adjust the measured values of spectral radiance factor of the specimens to be relative to freshly prepared smoked MgO. Each of the specimens was measured for two orientations; the first was with the specimen identification on the back of the specimen positioned so that it could be read when the specimen was mounted against the sample port of the integrating sphere and the second measurement with the specimen rotated clockwise 90° in its own plane. Zero calibration curves were recorded with the sample beam blocked.

3.3 Telecolorimeter Measurements for Nighttime Color

3.3.1 Color Measurements. Color measurements were made with a large variety of geometries. Using the procedures described below, in Section 5, Recommended Test Procedures, the color measurements were made on a Pritchard photometer and a Gamma photometer equipped with telescope and suitable tristimulus color filters which convert them into telecolorimeters.

The Gamma Telecolorimeter, Model 2009K, is manufactured by Gamma Scientific, Incorporated, 3777 Ruffin Road, San Diego, California 92123. The Pritchard Telecolorimeter is the Pritchard Photometer, Model Spectra 1980, equipped with tristimulus filters, and is manufactured by Photo Research, 3000 N. Hollywood Way, Burbank, California 91505.

3.3.2 Specific Intensity Measurements. Specific intensity measurements were made with the Pritchard and Gamma photometers, as described below in Section 5, Recommended Test Procedures. Only one geometric condition was used, that of 5/0.33.

4. Results Obtained in the Study

The colorimetric and photometric results obtained on the materials used in this study are given in this section.

4.1 Colorimetric Results

4.1.1 Daytime Color. The daytime color of the samples was obtained from the spectrophotometric measurements described in Section 3.2. The tristimulus values X, Y and Z and the chromaticity coordinates x, y, z were obtained by the CIE standard observer system by means of the following equations:

$$X = \int S(\lambda)\beta(\lambda)\bar{x}(\lambda)d\lambda$$

$$Y = \int S(\lambda)\beta(\lambda)\bar{y}(\lambda)d\lambda$$

$$Z = \int S(\lambda)\beta(\lambda)\bar{z}(\lambda)d\lambda$$

$$x = X/(X + Y + Z)$$

$$y = Y/(X + Y + Z)$$

$$z = Z/(X + Y + Z),$$

where

$S(\lambda)$ = spectral distribution of the source for daytime

$\beta(\lambda)$ = spectral radiance factors of the samples for diffuse irradiation

$\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ = spectral tristimulus values of the standard observer.

When the spectral radiance factor $\beta(\lambda)$ is used in the computation of tristimulus value Y, Y is called the luminance factor β. For daytime conditions the spectral distribution of the source was represented in the computations by CIE Source C and by CIE Source D_{65}. CIE Source C is intended to represent average daylight with a correlated color temperature of approximately 6774K. CIE Source D_{65} represents a phase of daylight with a correlated color temperature of approximately 6504K. CIE Source D_{65} incorporates atmospheric absorption bands as well as some ultraviolet radiation, but CIE Source C does not. (The International Commission on Illumination anticipated that at some future time Source C will be dropped from the list of standard illuminants.)

The spectral reflectance factors of the samples were obtained under conditions of diffuse illumination and unidirectional, 6° view. Table IV lists the results of chromaticity coordinates x, y and luminance factors β, obtained for the NBS set of retroreflective samples. Also listed for comparison are data, obtained on a photoelectric tristimulus colorimeter with 45° incidence angle and 0° viewing angle (45/0), as submitted by the manufacturer of the samples. Table V shows the ISCC-NBS color names and the Munsell notations of these samples derived from the colorimetric data obtained under D/0 and 45/0 geometry for CIE Source C. Figure 12 shows for four red retroreflectors, a typical plot of the chromaticity coordinates of the samples obtained under these two geometric conditions. The solid lines are NJCUTCD specification for red surface colors, and the dashed lines are boundaries proposed by 3M for daylight red retroreflector specifications in L-S-300B.

4.1.2 Nighttime Color. If spectral reflectance factor data were obtained on a spectroradiometer or spectrophotometer that simulates nighttime geometry, the equations given in 4.1.1 would apply to the computation of nighttime color. The spectral distribution of the source in this application would be that of 2856K.

The colorimetric data x, y obtained with the NBS set of samples for several geometric conditions are listed in Table VI. The particular geometry is indicated by the entrance angle over the observation angle. Thus an entrance angle of say 5° and an observation angle of say 0.33° is shown as 5/0.33.

Table VII shows the colorimetric data x, y obtained with the Interlaboratory set of samples for a 0.33° observation angle and entrance angles of -4°, 5°, and 10°.

It has been shown by several investigations that the nighttime color varies slightly with entrance angle and with observation angle. We have also found this effect as is shown on Figure 13 for blue retroreflectors and on Figure 14 for white and silver retroreflectors. Boundary lines on these figures are those recommended in Section 6.2.2.

For the interlaboratory study it was suggested that one entrance angle, 5°, and one observation angle, 0.33°, designated 5/0.33, be used. But as seen in Figure 14, if the data are close to the edge of the tolerance area for one geometry some data may fall outside, for another

Table IV. Chromaticity Coordinates and Reflectance Factor for Daytime Conditions

Manufacturer's Identity †	No.	Source C* D/0 x	y	β(%)	Source D_{65}* D/0 x	y	β(%)	Source C 45/0** x	y	β(%)	Color Names Submitted by Manufacturer
S	3302	0.625	0.311	5.42	0.626	0.314	5.32	0.654	0.324	4.29	Red
S	3282	.621	.322	7.59	.622	.324	7.48	.654	.318	5.59	Ruby Red
S	3272	.593	.339	12.09	.594	.342	11.92	.614	.335	8.12	Red
A	238D	.616	.335	11.48	.617	.337	11.31	-	-	-	Red
S	3872	.622	.329	6.34	.624	.321	6.23	.639	.331	4.45	Red
M	12A-R	.573	.326	3.98	.575	.329	3.93	-	-	-	Red
M	12A-A	.541	.408	11.94	.542	.410	11.68	-	-	-	Amber
S	3279	.481	.377	6.51	.482	.384	6.47	.489	.379	5.95	Brown
S	3884	.547	.397	22.41	.548	.399	21.96	.552	.395	19.04	Orange
S	3284	.546	.387	25.56	.547	.390	25.10	.569	.386	23.01	Orange
A	240E	.562	.397	26.44	.564	.398	25.88	-	-	-	Orange
S	FEA588	.565	.393	21.40	.565	.395	21.14	.572	.389	20.26	Orange
S	3871	.523	.457	26.52	.522	.459	26.16	.528	.467	21.99	Yellow
S	3271	.491	.470	38.03	.490	.474	37.70	.499	.474	35.15	Yellow
S	FEA675	.489	.462	39.33	.487	.465	38.94	.495	.464	34.50	Yellow
A	242C	.487	.470	43.62	.485	.473	43.23	-	-	-	Yellow
S	RF151	.417	.449	63.30	.415	.457	63.37	.437	.464	57.04	Yellow
S	3273	.429	.414	30.15	.429	.421	30.02	.435	.415	24.55	Gold
S	3281	.449	.497	44.88	.445	.503	44.99	.443	.519	40.97	Lemon Yellow
S	3877	.168	.417	9.84	.168	.435	10.10	.154	.430	6.53	Green
S	3277	.157	.422	8.59	.156	.440	8.82	.126	.414	5.71	Green

* See Section 4.1

** Data Submitted by Manufacturer.

† S, 3-M Scotchlite; A, American Decal; M, Amerace Stimsonite.

Table IV. (Continued)

Manufacturer's Identity †	No.	Source C* D/0 x	y	β(%)	Source D_{65}* D/0 x	y	β(%)	Source C 45/0** x	y	β(%)	Color Names Submitted by Manufacturer
A	Green	0.141	0.436	9.27	0.140	0.454	9.54	-	-	-	Green
M	PMO-M	.213	.330	14.93	.213	.346	15.08	-	-	-	Green
M	PMO-M/B	.209	.329	15.23	.210	.344	15.38	-	-	-	Green
S	3276	.216	.244	8.20	.218	.258	8.26	0.277	0.286	6.43	Gray-Blue
S	3275	.155	.135	3.54	.156	.143	3.52	.145	.115	2.05	Blue
S	FEA681	.147	.143	8.28	.146	.155	8.36	.136	.152	6.70	Blue
S	RF150	.312	.320	75.73	.315	.333	75.73	.326	.319	68.25	White
S	3300	.307	.314	46.89	.309	.327	46.90	.308	.314	46.58	White
A	229E	.311	.322	58.35	.314	.336	58.36	-	-	-	White
S	3870	.299	.307	39.19	.301	.320	39.21	.303	.310	31.74	Silver
M	2400	.301	.309	20.69	.304	.322	20.70	-	-	-	Crystal
M	FOS975	.303	.310	22.72	.306	.323	22.73	-	-	-	Crystal
S	3280	.320	.339	54.62	.322	.351	54.64	.319	.342	39.05	Imperial White
S	FEA556	.324	.345	49.10	.326	.357	49.12	.333	.356	37.15	Silver
S	3070	.326	.346	51.44	.328	.358	51.45	.327	.347	45.30	Silver
S	3270	.327	.349	54.39	.329	.361	54.42	.328	.355	42.51	Silver
S	3285	.313	.322	2.57	.316	.335	2.57	NA	NA	NA	Black

* See Section 4.1

** Data Submitted by Manufacturer.

† S, 3-M Scotchlite; A, American Decal; M, Amerace Stimsonite

Table V. Munsell and ISCC NBS Color Under Daytime Conditions

Manufacturer's Identity		Geometry, D/O			Geometry, 45/0		
		Munsell Notation	ISCC/NBS Color		Munsell Notation	ISCC/NBS Color	
Color	* No.		No.	Name		No.	Name
Red	S 3302	8.3R 2.7/11.8	11	Vivid Red	0.4 YR 2.4/11.7	41	Deep Reddish Brown
Ruby Red	S 3282	8.2R 3.2/12.8	11	Vivid Red	9.4 R 2.8/12.9	40	Strong Reddish Brown
Red	S 3272	8.4R 4.0/13.5	11	Vivid Red	9.2 R 3.3/12.5	40	Strong Reddish Brown
Red	A 238D	8.5R 3.9/14.6	11	Vivid Red	-	-	-
Red	S 3872	9.2R 3.0/11.7	40	Strong Reddish Brown	0.5 YR 2.5/11.1	41	Deep Reddish Brown
Red	M 12A-R	9.3R 2.3/8.6	41	Deep Reddish Brown	-	-	-
Amber	M 12A-A	4.9 YR 4.0/9.8	55	Strong Brown	-	-	-
Brown	S 3279	3.9 YR 3.0/5.5	55	Strong Brown	4.0 YR 2.9/5.6	55	Strong Brown
Orange	S 3884	3.1 YR 5.3/12.5	51	Deep Orange	2.9 YR 4.9/12.2	51	Deep Orange
Orange	S 3284	2.0 YR 5.6/13.0	34	Vivid Reddish Orange	1.6 YR 5.3/14.3	34	Vivid Reddish Orange
Orange	A 240E	2.6 YR 5.7/14.6	48	Vivid Orange	-	-	-
Orange	S FEA588	2.3 YR 5.2/13.7	51	Deep Orange	2.0 YR 5.1/14.0	34	Vivid Reddish Orange
Yellow	S 3871	9.4 YR 5.7/13.4	69	Deep Orange Yellow	0.3 Y 5.2/13.6	74	Strong Yellowish Brown
Yellow	S 3271	2.2 Y 6.6/12.7	82	Vivid Yellow	2.1 Y 6.4/13.3	82	Vivid Yellow
Yellow	S FEA675	1.5 Y 6.7/12.2	82	Vivid Yellow	1.5 Y 6.4/12.3	82	Vivid Yellow
Yellow	A 242C	2.3 Y 7.0/12.8	8	Vivid Yellow	-	-	-
Yellow	S RF151	6.4 Y 8.2/8.7	83	Brilliant Yellow	5.6 Y 7.9/10.0	84	Strong Yellow
Gold	S 3273	1.1 Y 6.0/6.4	88	Dark Yellow	0.8 Y 5.5/6.2	74	Strong Yellowish Brown
Lem.Yel.	S 3281	7.8 Y 7.1/11.6	97	Vivid Greenish Yel.	0.2 GY 6.9/12.4	97	Vivid Greenish Yellow
Green	S 3877	9.0 G 3.6/11.2	139	Vivid Green	8.5 G 3.0/11.5	139	Vivid Green
Green	S 3277	9.0 G 3.4/11.8	139	Vivid Green	10 G 2.8/12.6	158	Vivid Bluish Green
Green	A Green	8.8 G 3.5/13.5	139	Vivid Green	-	-	-

* S, 3-M Scotchlite; A, American Decal; M, Amerace Stimsonite

Table V. (Continued)

Manufacturer's Identity		Geometry, D/0			Geometry, 45/0		
		Munsell Notation	ISCC/NBS Color		Munsell Notation	ISCC/NBS Color	
Color	* No.		No.	Name		No.	Name
Green	M PMO-M	4.5 BG 4.4/7.1	160	Strong Bluish Green	-	-	-
Green	M PMO-M/B	4.7 BG 4.7/7.3	160	Strong Bluish Green	-	-	-
Gray Blue	S 3276	9.2 B 3.3/4.9	186	Grayish Blue	2.3 PB 3.0/1.5	192	Dark Bluish Gray
Blue	S 3275	4.7 PB 2.2/9.6	179	Deep Blue	4.9 PB 1.5/9.4	179	Deep Blue
Blue	S FEA681	3.1 PB 3.3/12.7	178	Strong Blue	0.8 PB 3.0/11.3	178	Strong Blue
White	S RF150	4.2 GY 8.9/0.2	263	White	5.1 R 8.5/1.1	10	Pinkish Gray
White	S 3300	8.8 B 7.3/0.4	264	Light Gray	5.8 PB 7.4/0.3	264	Light Gray
White	A 229E	9.3 GY 8.0/0.4	264	Light Gray	-	-	-
Silver	S 3870	2.5 PB 6.7/1.3	190	Light Bluish Gray	3.2 PB 6.1/0.7	191	Bluish Gray
Crystal	M 2400	1.3 PB 5.1/0.7	191	Bluish Gray	-	-	-
Crystal	M FOS975	2.6 PB 5.3/0.6	191	Bluish Gray	-	-	-
Imperial White	S 3280	5.4 GY 7.7/1.2	154	Light Greenish Gray	6.4 GY 6.7/1.3	122	Grayish Yellow Green
Silver	S FEA556	4.2 GY 7.4/1.4	122	Grayish Yellow Green	1.9 GY 6.7/1.9	122	Grayish Yellow Green
Silver	S 3070	3.2 GY 7.5/1.5	121	Pale Yellow Green	2.8 GY 7.2/1.5	122	Grayish Yellow Green
Silver	S 3270	4.1 GY 7.7/1.7	121	Pale Yellow Green	5.0 GY 7.0/1.9	122	Grayish Yellow Green
Black	S 3285	2.8 GY 1.8/0.2	267	Black	-	-	-

* S, 3-M Scotchlite; A, American Decal; M, Amerace Stimsonite

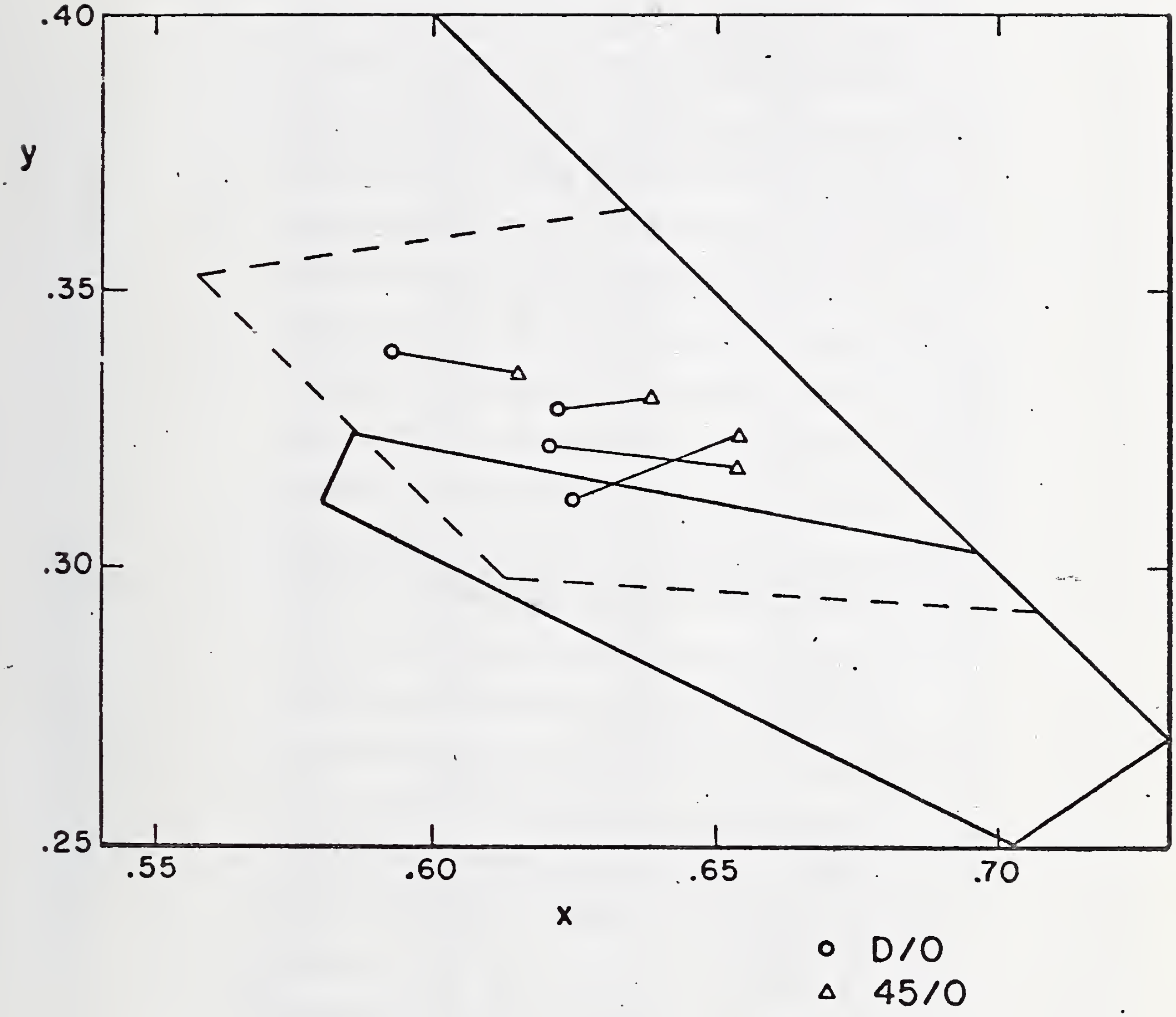


Figure 12. Chromaticity differences between D/O and 45/O geometries for red "engineering" grade and "high intensity" grade retroreflective sheeting materials. Boundaries on this figure are: solid line, NJCUTCD for daytime red surface colors; dashed line, 3M proposed for L-S-300B red retroreflectors in daylight.

Table VI. Colorimetric Data of the NBS Samples for Several Geometries

Manufacturer's Identity † No.	Manufacturer's Color Name	-4/0.2 x	-4/0.2 y	15/0.2 x	15/0.2 y	30/0.2 x	30/0.2 y
S3282	Ruby Red	0.647	0.342	0.646	0.339	0.655	0.333
S3272	Red	.623	.352	.628	.352	.640	.344
A230D	Red	-	-	-	-	-	-
S3872	Red	.654	.334	.652	.335	.655	.333
M12A-R	Red	.652	.324	.676	.313	.665	.324
M12A-A	Amber	.597	.450	.592	.463	.594	.461
S3279	Brown	.610	.383	.627	.377	.632	.372
S3884	Orange	.600	.394	.601	.395	.599	.395
S3284	Orange	.548	.409	.557	.407	.568	.404
A240E	Orange	-	-	-	-	-	-
SPEA588	Orange	.593	.408	.593	.408	.597	.404
S3871	Yellow	.533	.464	.532	.464	.532	.466
S3273	Yellow	.531	.459	.538	.460	.534	.458
SPEA675	Yellow	.533	.452	.535	.451	.535	.453
A242C	Yellow	-	-	-	-	-	-
SRP151	Yellow	.435	.437	.430	.437	.413	.437
S3273	Gold	.465	.463	.468	.465	.470	.476
S3281	Lemon Yellow	.522	.466	.525	.463	.526	.463
S3877	Green	.171	.522	.169	.521	.166	.516
S3277	Green	.210	.592	.163	.642	.164	.594
A-Green	Green	-	-	-	-	-	-
MPMO-M	Green	.281	.507	.270	.508	.264	.500
MPMO-M/B	Green	.273	.504	.270	.505	.266	.503
S3276	Grey, Blue	.147	.342	.145	.346	.147	.364
S3275	Blue	.115	.236	.108	.235	.102	.253
SPEA681	Blue	.136	.308	.115	.309	.114	.298
SRP150	White	.442	.434	.430	.435	.414	.425
A229E	White	-	-	-	-	-	-
S3870	Silver	.399	.416	.400	.415	.306	.410
M2400	Crystal	.422	.426	.426	.411	.419	.427
MPGS975	Crystal	.432	.417	.436	.407	.438	.308
S3280	Imper.White	.403	.411	.409	.418	.427	.436
SPEA556	Silver	.422	.431	.432	.441	.457	.451
S3070	Silver	.413	.410	.409	.433	.406	.426
S3270	Silver	.422	.435	.434	.439	.453	.449
S3285	Black	.444	.447	.453	.447	.502	.491

Manufacturer's Identity † No.	Manufacturer's Color Name	-4/0.33 x	-4/0.33 y	5/0.33 x	5/0.33 y	10/0.33 x	10/0.33 y
S3282	Ruby Red	0.660	0.339	0.660	0.339	0.662	0.337
S3272	Red	.634	.362	.635	.361	.638	.358
A230D	Red	.622	.369	.617	.374	.621	.371
S3872	Red	.655	.343	.655	.341	.657	.341
M12A-R	Red	.672	.328	.671	.329	.670	.330
M12A-A	Amber	.592	.408	.592	.408	.593	.407
S3279	Brown	.623	.370	.621	.373	.625	.369
S3884	Orange	.618	.373	.607	.304	.608	.367
S3284	Orange	.547	.405	.549	.400	.550	.405
A240E	Orange	.599	.376	.596	.378	.598	.376
SPEA588	Orange	.595	.401	.592	.405	.597	.399
S3871	Yellow	.544	.455	.540	.459	.542	.457
S3273	Yellow	.534	.458	.532	.460	.542	.450
SPEA675	Yellow	.533	.452	.534	.451	.536	.450
A242C	Yellow	.537	.438	.533	.441	.533	.443
SRP151	Yellow	.439	.422	.439	.423	.436	.423
S3273	Gold	.497	.422	.488	.434	.496	.425
S3281	Lemon Yellow	.523	.466	.519	.470	.526	.463
S3877	Green	.168	.530	.171	.525	.168	.529
S3277	Green	.202	.591	.204	.586	.200	.592
A-Green	Green	.186	.600	.188	.595	.187	.603
MPMO-M	Green	.271	.475	.272	.474	.272	.472
MPMO-M/B	Green	.236	.435	.236	.416	.236	.416
S3276	Grey, Blue	.125	.324	.126	.324	.126	.326
S3275	Blue	.305	.230	.106	.228	.304	.230
SPEA681	Blue	.093	.308	.095	.308	.094	.308
SRP150	White	.444	.429	.444	.428	.442	.432
A229E	White	.433	.424	.429	.422	.434	.422
S3870	Silver	.398	.412	.395	.410	.396	.432
M2400	Crystal	.412	.406	.412	.406	.412	.405
MPGS975	Crystal	.418	.412	.420	.409	.423	.406
S3280	Imper.White	.399	.406	.400	.408	.401	.409
SPEA556	Silver	.417	.425	.412	.425	.421	.427
S3070	Silver	.406	.432	.401	.425	.404	.433
S3270	Silver	.428	.437	.426	.434	.435	.438
S3285	Black	.450	.442	.450	.441	.455	.440

Manufacturer's Identity † No.	Manufacturer's Color Name	-4/0.5 x	-4/0.5 y	10/0.5 x	10/0.5 y	15/0.5 x	15/0.5 y	30/0.5 x	30/0.5 y
S3282	Ruby Red	0.662	0.337	0.662	0.337	0.662	0.337	0.656	0.343
S3272	Red	.636	.360	.638	.358	.641	.355	.647	.351
A230D	Red	.614	.376	.620	.371	.616	.375	.620	.374
S3872	Red	.655	.343	.657	.341	.656	.342	.658	.341
M12A-R	Red	.672	.328	.672	.328	.672	.328	.675	.325
M12A-A	Amber	.595	.404	.593	.406	.597	.402	.597	.402
S3279	Brown	.617	.375	.621	.372	.622	.372	.630	.361
S3884	Orange	.610	.381	.614	.378	.613	.379	.612	.381
S3284	Orange	.545	.403	.548	.402	.549	.404	.564	.390
A240E	Orange	.597	.376	.593	.380	.595	.379	.598	.379
SPEA588	Orange	.594	.403	.594	.402	.594	.403	.596	.401
S3871	Yellow	.546	.453	.546	.452	.547	.452	.547	.451
S3273	Yellow	.529	.463	.535	.457	.537	.455	.543	.450
SPEA675	Yellow	.536	.449	.537	.449	.535	.450	.534	.453
A242C	Yellow	.537	.438	.538	.437	.535	.441	.540	.439
SRP151	Yellow	.447	.421	.448	.421	.448	.422	.430	.421
S3273	Gold	.489	.432	.492	.432	.490	.435	.503	.437
S3281	Lemon Yellow	.523	.466	.524	.465	.526	.463	.531	.459
S3877	Green	.171	.525	.172	.524	.370	.325	.168	.527
S3277	Green	.204	.591	.207	.589	.203	.592	.203	.591
A-Green	Green	.192	.595	.190	.600	.193	.601	.193	.630
MPMO-M	Green	.272	.478	.272	.477	.272	.476	.263	.463
MPMO-M/B	Green	.270	.473	.271	.471	.271	.473	.266	.471
S3276	Grey, Blue	.128	.327	.129	.329	.128	.334	.132	.349
S3275	Blue	.108	.234	.108	.236	.108	.238	.110	.243
SPEA681	Blue	.094	.296	.095	.296	.094	.299	.091	.292
SRP150	White	.444	.421	.446	.422	.446	.426	.424	.424
A229E	White	.427	.414	.435	.421	.435	.420	.431	.417
S3870	Silver	.399	.406	.400	.405	.400	.406	.393	.410
M2400	Crystal	.422	.404	.418	.406	.419	.406	.418	.405
MPGS975	Crystal	.423	.406	.427	.404	.426	.405	.432	.405
S3280	Imper.White	.402	.407	.404	.409	.408	.412	.426	.428
SPEA556	Silver	.412	.424	.417	.424	.424	.428	.452	.440
S3070	Silver	.401	.421	.398	.421	.398	.422	.398	.437
S3270	Silver	.423	.431	.426	.433	.433	.434	.456	.441
S3285	Black	.456	.439	.457	.440	.461	.439	.474	.438

Manufacturer's Identity † No.	Manufacturer's Color Name	-4/2 x	-4/2 y	10/2 x	10/2 y	15/2 x	15/2 y	30/2 x	30/2 y
S3282	Ruby Red	0.659	0.339	0.660	0.338	0.660	0.338	0.672	0.327
S3272	Red	.647	.348	.645	.351	.644	.352	.643	.353
A230D	Red	.629	.368	.630	.366	.627	.368	.632	.364
S3872	Red	.661	.336	.657	.340	.660	.337	.656	.342
M12A-R	Red	.659	.336	.673	.327	.666	.333	.662	.338
M12A-A	Amber	.590	.409	.592	.408	.591	.409	.576	.424
S3279	Brown	.623	.363	.632	.360	.631	.363	.622	.348
S3884	Orange	.626	.367	.628	.367	.629	.366	.628	.367
S3284	Orange	.554	.380	.555	.379	.554	.383	.556	.387
A240E	Orange	.609	.376	.610	.377	.610	.376	.609	.377
SPEA588	Orange	.606	.390	.606	.391	.606	.391	.610	.388
S3871	Yellow	.573	.425	.564	.435	.574	.424	.567	.432
S3273	Yellow	.552	.441	.552	.441	.552	.440	.554	.440
SPEA675	Yellow	.546	.442	.545	.443	.548	.440	.552	.436
A242C	Yellow	.545	.438	.546	.437	.546	.438	.549	.436
SRP151	Yellow	.434	.419	.436	.418	.438	.419	.446	.426
S3273	Gold	.522	.426	.524	.424	.524	.425	.528	.428
S3281	Lemon Yellow	.533	.457	.533	.457	.529	.461	.537	.454
S3877	Green	.385	.550	.382	.552	.382	.552	.178	.552
S3277	Green	.202	.599	.201	.600	.201	.600	.200	.606
A-Green	Green	.195	.623	.188	.606	.392	.622	.188	.624
MPMO-M	Green	.272	.469	.274	.468	.272	.470	.268	.472
MPMO-M/B	Green	.254	.474	.269	.465	.268	.467	.265	.467
S3276	Grey, Blue	.169	.392	.162	.393	.160	.391	.152	.381
S3275	Blue	.108	.305	.307	.304	.105	.297	.102	.280
SPEA681	Blue	.106	.265	.101	.261	.100	.260	.100	.254
SRP150	White	.411	.407	.411	.399	.412	.398	.421	.406
A229E	White	.454	.418	.455	.439	.455	.420	.447	.423
S3870	Silver	.450	.402	.448	.402	.445	.401	.479	.403
M2400	Crystal	.413	.402	.412	.401	.432	.399	.417	.400
MPGS975	Crystal	.408	.392	.433	.393	.416	.389	.429	.402
S3280	Imper.White	.450	.438	.450	.435	.452	.433	.457	.426
SPEA556	Silver	.472	.435	.474	.431	.472	.429	.468	.426
S3070	Silver	.468	.426	.468	.427	.469	.427	.462	.434
S3270	Silver	.477	.425	.477	.425	.474	.423	.468	.427
S3285	Black	.456	.410	.457	.414	.467	.420	.471	.425

† S, 3-M Scotchlite; A, American Decal; M, Amerace Stimsonite

Table VII. Colorimetric Data of the Interlaboratory Samples

Sample No.	-4/0.33		5/0.33		10/0.33	
	x	y	x	y	x	y
1	0.419	0.426	0.421	0.423	0.419	0.425
2	.413	.415	.412	.418	.412	.418
3	.390	.404	.392	.402	.394	.406
4	.456	.449	.458	.447	.463	.444
5	.417	.436	.418	.438	.422	.439
6	.444	.432	.463	.450	.466	.450
7	.530	.469	.533	.465	.533	.466
8	.538	.461	.538	.460	.538	.461
9	.535	.458	.536	.453	.536	.457
10	.512	.477	.514	.474	.515	.474
11	.540	.454	.540	.454	.544	.450
12	.566	.430	.564	.431	.566	.430
13	.658	.341	.656	.342	.657	.342
14	.631	.363	.632	.362	.633	.362
15	.654	.345	.654	.344	.654	.345
16	.627	.366	.628	.366	.629	.366
17	.643	.352	.644	.352	.646	.349
18	.655	.341	.657	.341	.656	.341
19	.643	.351	.642	.354	.646	.348
20	.677	.323	.673	.326	.672	.326
21	.100	.310	.099	.310	.099	.307
22	.104	.244	.106	.242	.110	.242
23	.107	.268	.108	.267	.108	.269
24	.112	.351	.112	.350	.111	.350
25	.086	.257	.087	.256	.086	.256
26	.086	.202	.087	.203	.085	.204
27	.083	.252	.082	.252	.081	.252
28	.172	.537	.172	.538	.171	.536
29	.190	.545	.190	.544	.190	.540
30	.217	.593	.216	.592	.214	.595
31	.196	.577	.196	.579	.194	.580
32	.186	.559	.185	.562	.185	.561
33	.173	.590	.171	.592	.172	.589
34	.167	.611	.166	.611	.167	.610
35	.181	.643	.180	.642	.181	.646
36	.618	.377	.618	.378	.616	.379
37	.628	.370	.627	.370	.629	.369
38	.535	.401	.534	.400	.537	.400
39	.515	.390	.512	.392	.516	.391
40	.570	.390	.572	.388	.572	.389
41	.559	.373	.555	.374	.561	.374
42	.620	.374	.622	.372	.620	.374
43	.582	.385	.582	.386	.583	.385
44	.592	.382	.596	.379	.596	.380

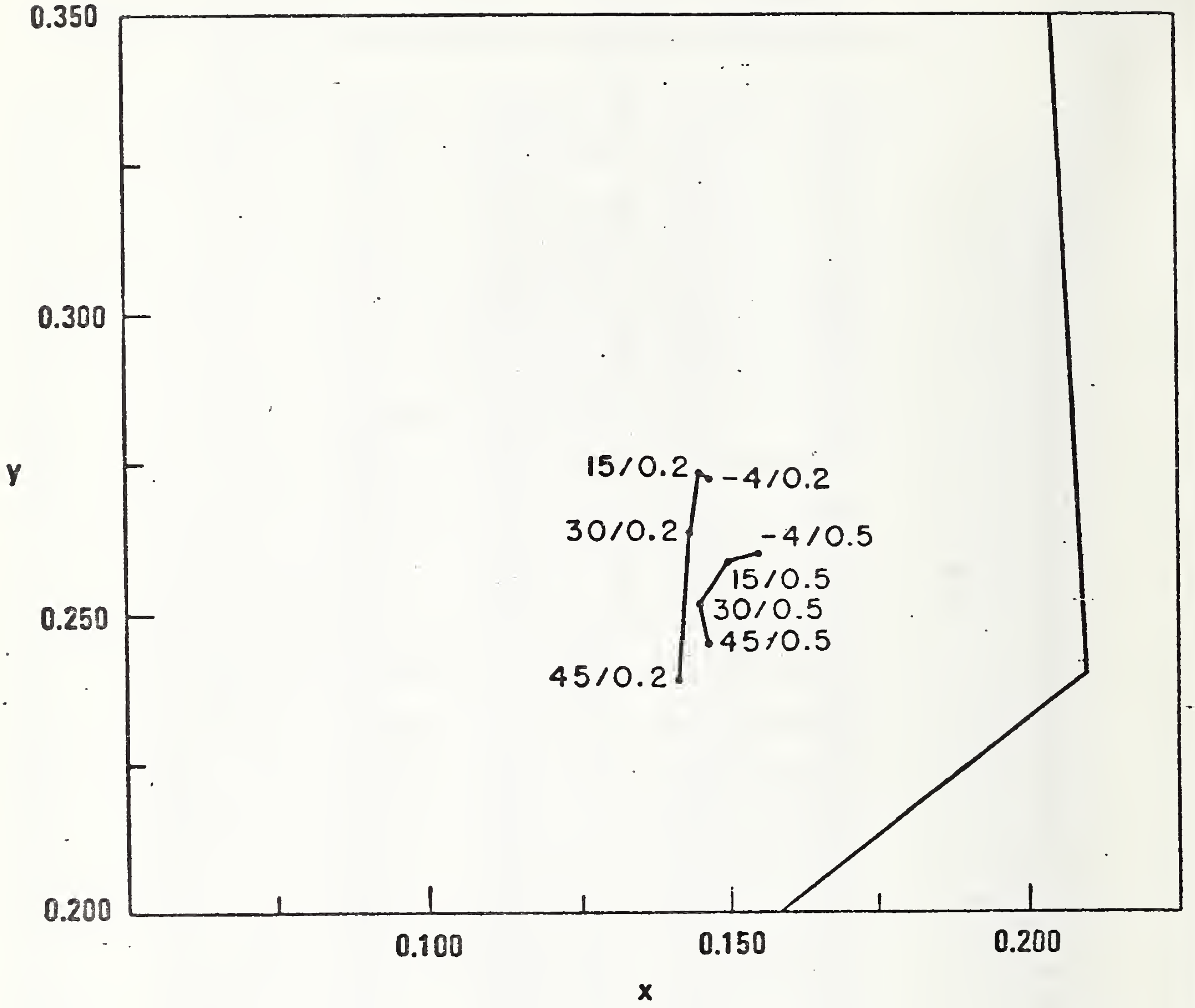


Figure 13. Chromaticity changes with change in entrance and observation angles for a blue retroreflector. Boundary on this figure is 3M recommended limit for nighttime conditions.

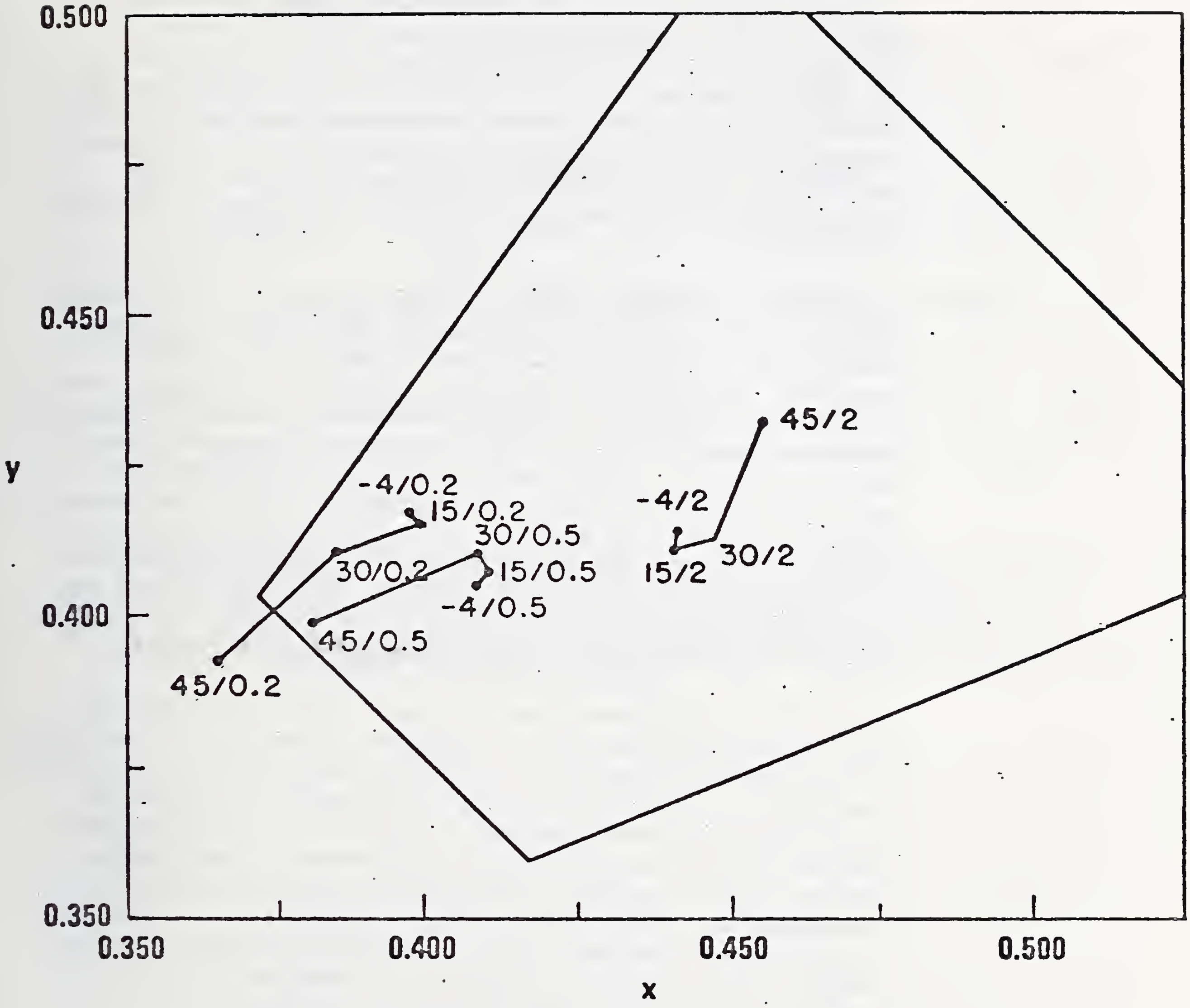


Figure 14. Chromaticity changes with change in entrance and observation angles for a white retroreflector. Boundary on this figure is 3M recommended limit for nighttime conditions.

geometry. Hence, we may conclude that color measured under one geometry may not be adequate.

The tristimulus-value correction factors of the telecolorimeters used in this study are listed in Table VIII. For the Gamma telecolorimeter these factors listed represent the correction factor for electrical trimming of the responses. For the Pritchard telecolorimeter the factors listed represent the correction factors for mathematically trimmed responses. Mathematical trimming was necessary on the Pritchard instrument because it had been designed as a telephotometer and tristimulus filters were added.

4.1.3 Variability of Nighttime Color Measurements. To determine how well color measurements can be replicated, the variability of measurements for one geometry 5/0.33 was studied. Two sets of measurements were made on one instrument at the National Bureau of Standards, a set of measurements was made on each of two different instruments at the National Bureau of Standards and a set of measurements were made on each of three instruments, two at the National Bureau of Standards and one in another laboratory. The variabilities of the measurements for these combinations, represented by the average standard deviations $\bar{\sigma}$ and the average coefficient of variation, $V = (\bar{\sigma}/\text{Mean})$ for several samples of each nominal color, are listed in Table IX.

The following figures show the data obtained on the two NBS telecolorimeters and at another laboratory on one telecolorimeter for the retroreflective materials on the Interlaboratory set of samples for one geometry. Figure 15 shows the colorimeter results (chromaticity coordinates) for the silver and white retroreflectors. The circles represent the average chromaticity measured on the three instruments. Also shown on this figure are the difference between the three measurements and their average for one sample. The differences among the measurements for the other samples of this color in the Interlaboratory Set is similar to the one shown. The standard deviations in x and y are also shown in this figure's caption.

The results obtained for the other colors are shown in Figure 16 for red, Figure 17 for orange, Figure 18 for yellow, Figure 19 for green, Figure 20 for blue, retroreflectors. Boundary lines on Figure 15 through 20 are those recommended in Section 6.2.

Table VIII. Summary of Tristimulus-Value Correction Factors* of Trimmed Instruments for Several Colors

Color	Gamma Instrument F_X	Gamma Instrument F_Y	Gamma Instrument F_Z	Pritchard Instrument F_X	Pritchard Instrument F_Y	Pritchard Instrument F_Z
Red	0.893	0.948	0.266	0.902	0.917	0.166
Yellow/Orange	0.996	0.972	1.055	0.980	0.891	1.004
Green	1.002	1.051	0.882	0.817	0.940	0.934
Blue	0.707	0.944	0.921	0.594	0.691	0.941
White	1.000	0.998	0.953	0.957	0.974	0.989

*Not all of the correction factors for these instruments met the requirements discussed in section 5.2.4 below. Although correction factors F_Z for red samples, and F_X for blue samples are relatively unimportant, better approximations to the CIE functions can be achieved by the manufacturer.

Table IX. Summary of Variability of Color Measurements, Interlab. Set

Color	3 Inst., 2 Lab.		2 Inst., 1 Lab.		1 Inst., 1 Lab.	
	$\bar{\sigma}_x$	$\bar{\sigma}_y$	$\bar{\sigma}_x$	$\bar{\sigma}_y$	$\bar{\sigma}_x$	$\bar{\sigma}_y$
White	0.012	0.012	0.005	0.009	0.0012	0.0014
Yellow	.010	.011	.014	.015	.0015	.0020
Red	.014	.015	.016	.016	.0010	.0009
Blue	.006	.033	.004	.020	.0007	.0009
Green	.011	.026	.010	.018	.0005	.0010
Orange	.010	.015	.010	.011	.0012	.0010
Mn	0.010	0.019	0.010	0.015	0.0010	0.0012

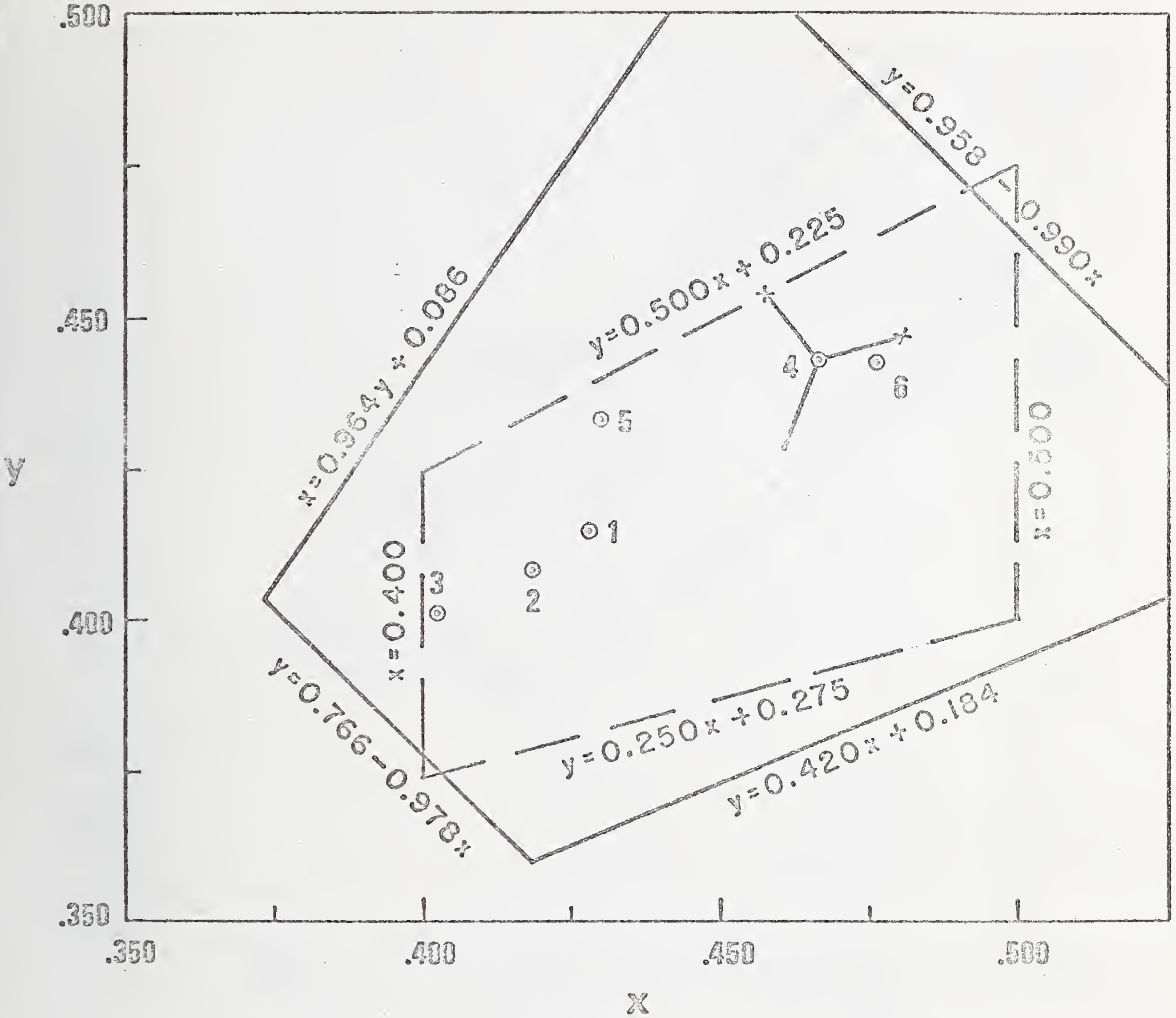


Figure 15. Chromaticity data for several white retroreflectors in the Interlaboratory set obtained on three different instruments. Geometry, 5/0.33. Average chromaticity obtained on the three instruments, ⊙. Chromaticity obtained for sample 4 on each instrument, •, +. X. Average standard deviations in x and y for all samples in this figure are $\bar{\sigma}_x = 0.012$ and $\bar{\sigma}_y = 0.012$. Boundaries are recommended limits for nighttime conditions: solid lines, 3M; dotted lines, NBS. Numbers refer to samples in Table III.

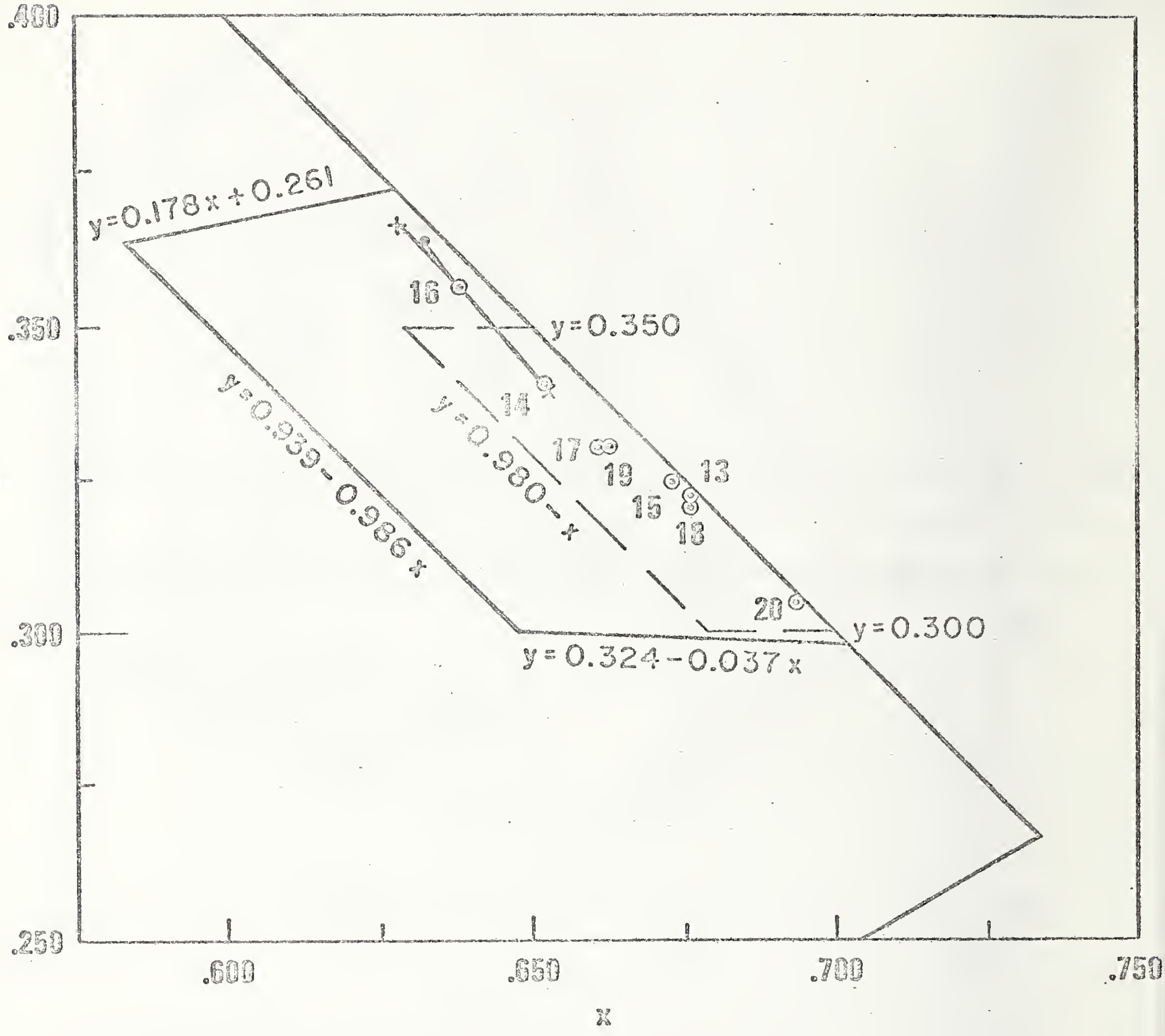


Figure 16. Chromaticity data for several red retroreflectors in the Interlaboratory set obtained on three different instruments. Geometry, 5/0.33. Average chromaticity obtained on the three instruments, ⊙. Chromaticity obtained for sample 16 on each instrument, ·, +, X. Average standard deviations in x and y for all samples in this figure are $\bar{\sigma}_x = 0.014$ and $\bar{\sigma}_y = 0.015$. Boundaries are recommended limits for nighttime conditions: solid lines, 3M; dotted lines, NBS. Numbers refer to samples in Table III.

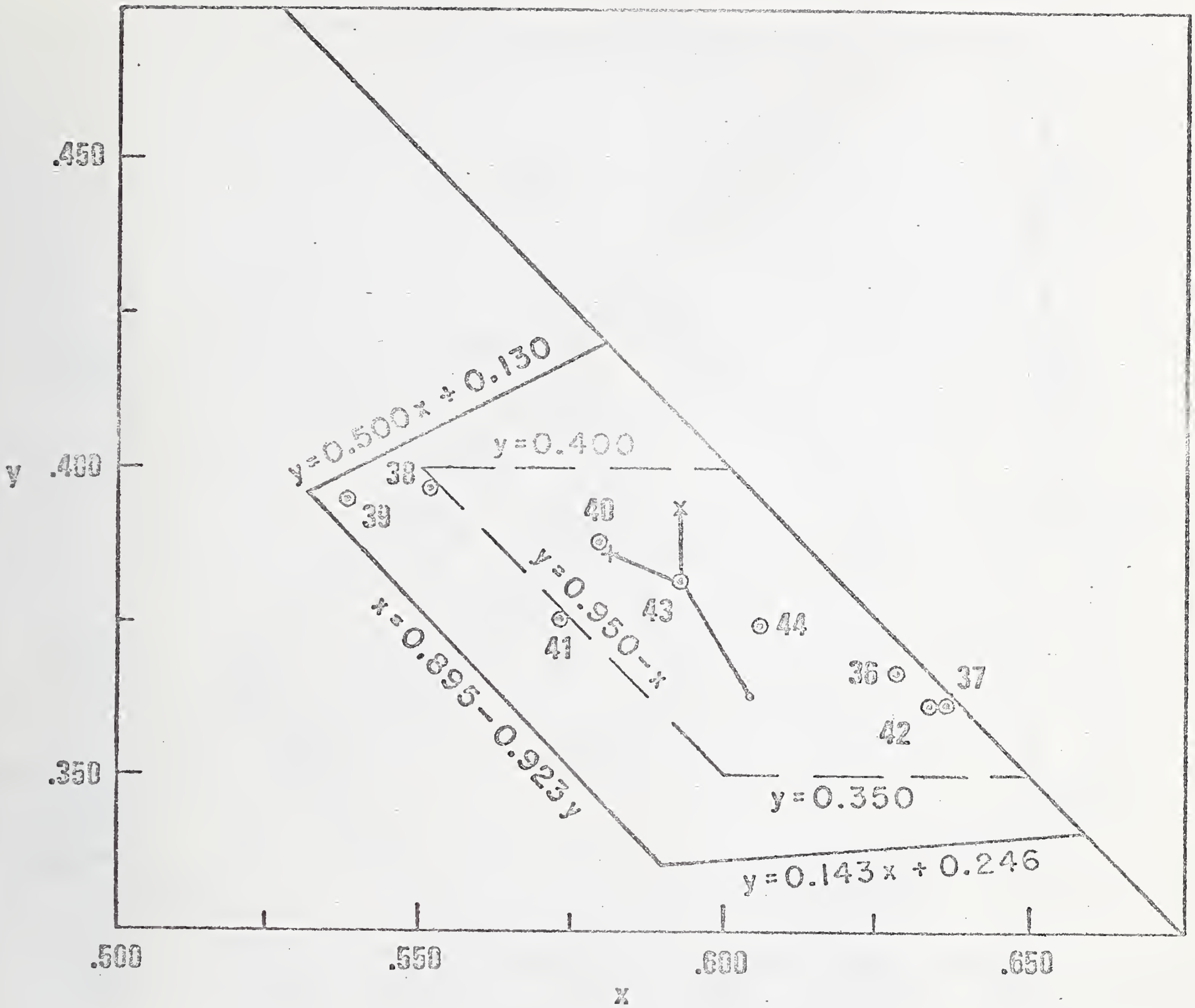


Figure 17. Chromaticity data for several orange retroreflectors in the Interlaboratory set obtained on three different instruments. Geometry, 5/0.33. Average chromaticity obtained on the three instruments, o. Chromaticity obtained for sample 43 on each instrument, ·, +, X. Average standard deviations in x and y for all samples in this figure are $\bar{\sigma}_x = 0.010$ and $\bar{\sigma}_y = 0.015$. Boundaries are recommended limits for nighttime conditions: solid lines, 3M; dotted lines, NBS. Numbers refer to samples in Table III.

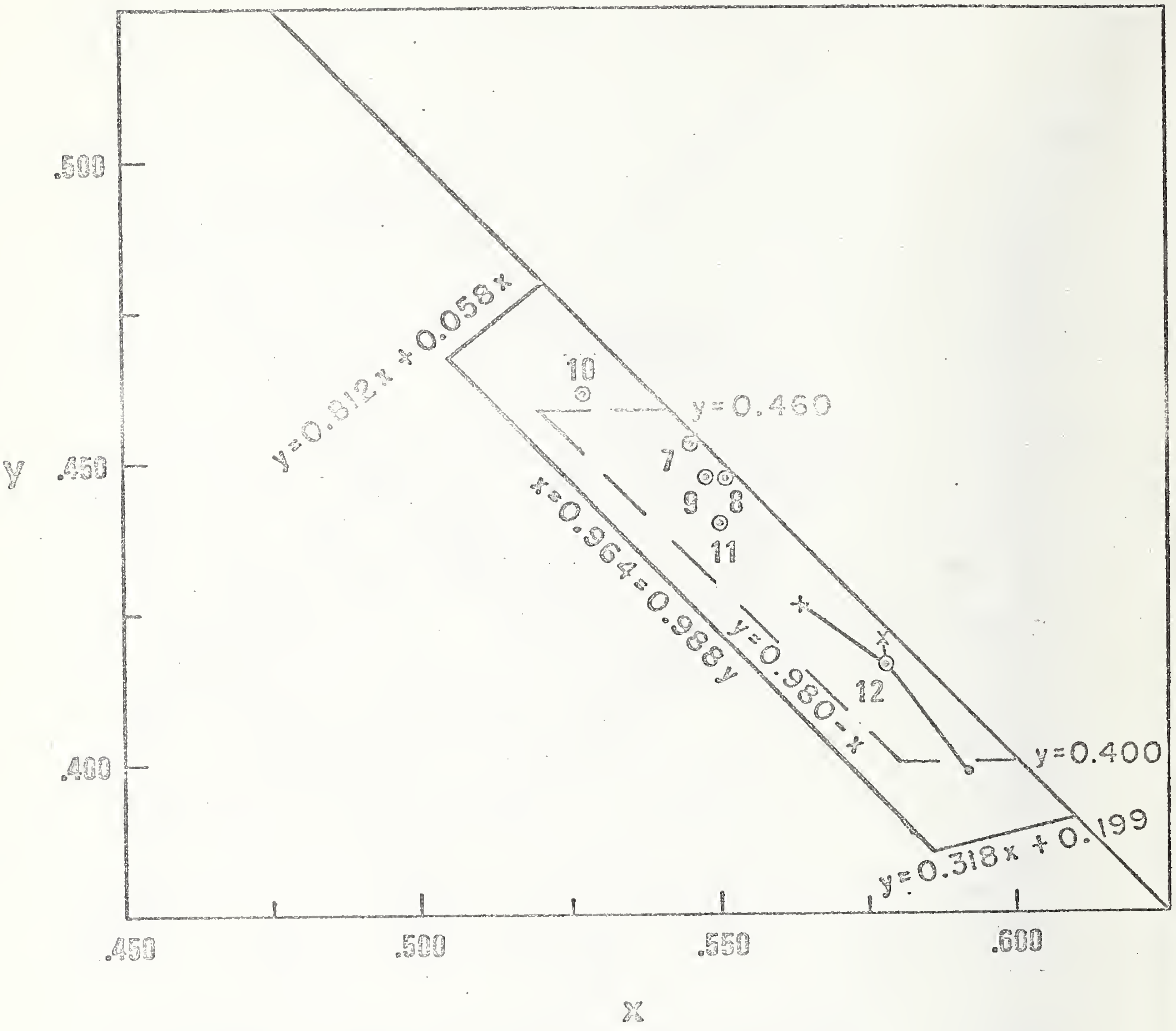


Figure 18. Chromaticity data for several yellow retroreflectors in the Interlaboratory set obtained on three different instruments. Geometry, 5/0.33. Average chromaticity obtained on the three instruments, ⊙. Chromaticity obtained for sample 12 on each instrument, ·, +, X. Average standard deviations in x and y for all samples in this figure are $\bar{\sigma}_x = 0.010$ and $\bar{\sigma}_y = 0.011$. Boundaries are recommended limits for nighttime conditions: solid lines, 3M; dotted lines, NBS. Numbers refer to samples in Table III.

Figure 19. Chromaticity data for several green retroreflectors in the Interlaboratory set obtained on three different instruments. Geometry, 5/0.33. Average chromaticity obtained on the three instruments, ⊙ . Chromaticity obtained for sample 31 on each instrument, ·, +, X. Average standard deviations in x and y for all samples in this figure are $\bar{\sigma}_x$ = .011 and $\bar{\sigma}_y$ = 0.026. Boundary is recommended limit for nighttime conditions by NBS and 3M. Numbers refer to samples in Table III.

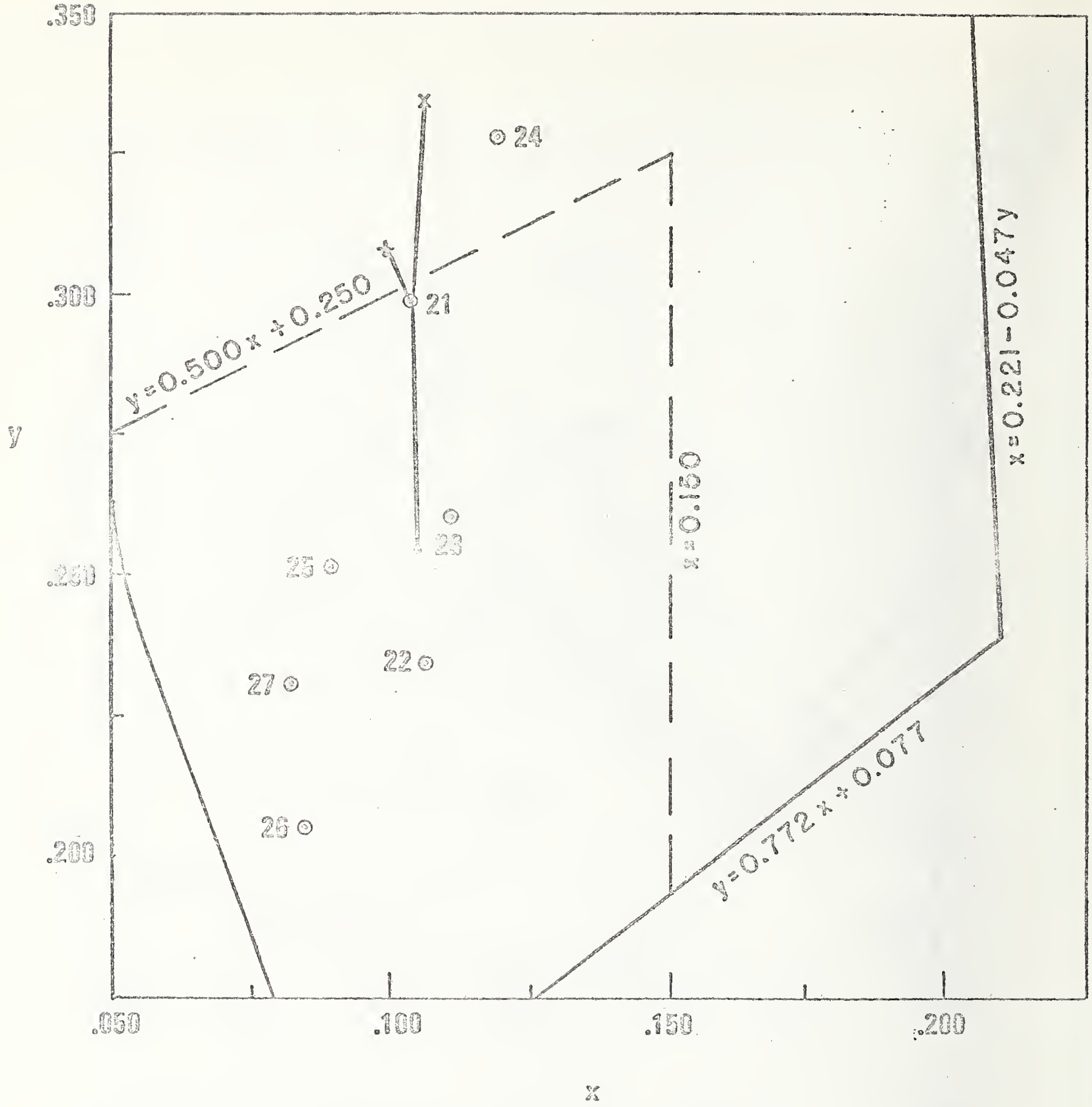


Figure 20. Chromaticity data for several blue retroreflectors in the Interlaboratory set obtained on three different instruments. Geometry, 5/0.33. Average chromaticity obtained on the three instruments, ʘ. Chromaticity obtained for sample 21 on each instrument, ·, +, X. Average standard deviations in x and y for all samples in this figure are $\bar{\sigma}_x = .006$ and $\bar{\sigma}_y = 0.033$. Boundaries are recommended limits for nighttime conditions: solid lines, 3M; dotted lines, NBS. Numbers refer to samples in Table III.

The variability among the colorimetric results obtained in this study is consistent with that obtained in earlier studies. It is our hope that as we improve our selection of reference calibration filters and our calibration techniques that this variability will be reduced.

4.2 Photometric Results

Under typical daytime conditions the luminance of a retroreflective sign, or legend, or other object is not a significant factor in determining visibility. Instead the contrast between an object or legend, and its background determines visibility. Since under most daylight conditions the illuminance on the object and on its background are equal and independent of distance, or nearly so, the contrast is a function only of the luminance factor of reflecting materials, such as retroreflectors and paints, is required for the evaluation of their daytime performance.

On the other hand, under nighttime conditions the luminance of a sign or object, or the intensity of a delineator, produced by the lights of an automobile varies inversely as the square of the distance. The luminance may be so low that the color of the object can not be recognized, or the object might not be seen. The luminance of the background is usually much lower than the luminance of a retroreflective sign or legend and has no significant effect on visibility.

If a retroreflective material under nighttime conditions has an area so small that it appears as a point source, for example a roadside delineator, its intensity, in candelas, is its pertinent photometric quantity. Therefore, its reflecting properties are characterized by the intensity produced by incident unit illuminance in candelas per footcandle, called specific intensity (abbreviated S.I.), or in international units candelas per lux, called coefficient of luminous intensity (abbreviated C.I.L.).

If a sign of retroreflective material is so large that it is seen as an object, rather than as a point, then the pertinent photometric quality is its luminance or candelas per unit area. Therefore, its reflecting properties are characterized by the luminance produced by incident unit illuminance in specific intensity per square foot, called specific intensity per unit area (abbreviated S.I.A.), or in international units coefficient of luminous intensity per unit area (abbreviated C.I.L./A or C.I.A.).

4.2.1 Daytime Luminance Factors. A measure of the daytime appearance of the color of retroreflectors other than its chromaticity is the luminance factor. Since the measured values of the luminance factor of retroreflective materials is very dependent upon the geometry of measurement, it is important that this geometry simulate the geometry of the use condition. Average luminance factors obtained for several colors are shown in Table X for two geometries, diffuse, 0° (D/0) and 45°, 0° (45/0). Also shown in this table for comparison are luminance factors, with D/0 and 0/45 geometries for similar materials obtained by A. Fisher, University of New South Wales, Australia, for the Standards Association of Australia and presented at the International Conference on Photometry and Colorimetry, Verna, Bulgaria, June, 1973. Geometries 0/45, used by Fisher, and 45/0, used by NBS, are expected to yield similar luminance factors.

4.2.2 Nighttime Specific Intensity per Unit Area. A measure of the nighttime appearance of a retroreflector is the specific intensity per unit area, S.I.A. = S.I./A. This quantity may be considered either as the luminance per unit illuminance $L' \cos \varepsilon_1 / E_n$ or the coefficient of luminous intensity per unit area, C.I.L./A or C.I.A. These two approaches lead to two methods of measurement. These may be called the luminance method (for large areas) or the intensity method (for small areas), respectively. The essential difference between these two methods is that in the luminance method this field stop is filled while in the intensity method the field is not. The units in either method can be either $cd/(fc \cdot ft^2)$ or $cd/(lx \cdot m^2)$.

Both of these methods were used in this study. It was found that the intensity method of measurement is in reasonably good agreement with the luminance method. The values for the NBS set are shown on Table XI for one instrument and geometry 5/0.33.

Table XII shows the C.I.L./A values obtained on the Interlaboratory Set for 5/0.33 geometry, using the intensity method. These values represent averages of measurements made with two instruments at NBS. The variability of these data are discussed in the next section.

Table X. Comparison of Daylight Luminance Factor, β, of Retroreflective Materials, NBS Set

Retroreflector Colors	Luminance Factor for D/0 and 45/0 Geometry					
	N B S			F I S H E R		
	No.	D/0	45/0	No.	D/0	0/45
Red	4	0.08	0.06	7	0.12	0.09
Brown	1	.065	.060	-	-	-
Orange	3	.23	.21	-	-	-
Yellow	6	.40	.36	6	.40	.34
Green	2	.09	.06	6	.09	.05
Blue	3	.07	.05	4	.03	.02
White	7	.53	.44	7	.51	.44

Table XI. Comparison of Specific Intensity per Unit Area Obtained by Two Methods. Geometry: 5/0.33, NBS Set

Manufacturer's Color Name	C.I.L./A* Luminance Method	C.I.L./A* Intensity Method
Ruby Red	41.2	39.3
Red	27.2	26.4
Red	18.2	17.6
Red	22.7	20.9
Brown	2.7	2.8
Orange	69.9	65.8
Orange	38.0	36.9
Orange	26.8	25.5
Orange	21.1	21.7
Yellow	142.9	138.3
Yellow	56.5	57.2
Yellow	56.0	55.2
Yellow	33.1	32.9
Yellow	68.7	64.3
Gold	70.4	69.4
Lemon Yellow	50.8	50.6
Green	40.6	44.1
Green	13.1	13.1
Green	16.6	17.8
Grey Blue	9.8	11.1
Blue	4.7	5.4
Blue	17.6	16.9
White	94.3	93.9
White	77.3	73.1
Silver	273.1	274.3
Imperial White	63.7	63.7
Silver	101.1	99.8
Silver	50.6	52.6
Silver	97.9	96.7
Black	18.4	18.6

* See Paragraph 4.2

Table XII. Specific Intensity per Unit Area by Intensity Method. Geometry: 5/0.33

Sample No.	and Color	C.I.L./A*
1	White	221.0
2	W	175.0
3	W	61.8
4	W	107.9
5	W	99.0
6	W	94.5
7	Yellow	126.6
8	Y	137.2
9	Y	57.6
10	Y	45.2
11	Y	53.1
12	Y	25.1
13	Red	42.2
14	R	21.1
15	R	19.0
16	R	23.0
17	R	18.8
18	R	26.5
19	R	12.0
20	R	12.9
21	Blue	20.9
22	B	6.3
23	B	9.7
24	B	22.9
25	B	6.0
26	B	3.8
27	B	4.8
28	Green	35.0
29	G	26.0
30	G	8.9
31	G	9.3
32	G	11.1
33	G	34.8
34	G	11.4
35	G	15.0
36	Orange	56.4
37	O	52.6
38	O	36.7
39	O	30.0
40	O	33.4
41	O	25.7
42	O	53.8
43	O	25.7
44	O	21.2

* See Paragraph 4.2.2

If the white and silver retroreflectors were spectrally nonselective there would be no need for correction factors in their photometry. But, as can be seen from Figure 3, these retroreflectors are not spectrally non-selective and require correction factors, as do retro-reflectors of other colors. Photometric correction factors for colored materials used for the data obtained on the Gamma and Pritchard Telecolorimeters are listed in Table XIII.

4.2.3 Variability of Nighttime Specific Intensity per Unit Area

To determine how well measurements of specific intensity per unit area are replicated, the variability for one geometry was studied. Two sets of measurements were made on one instrument at NBS, a set of measurements was made on two different instruments at NBS, and a set of measurements was made on each of three instruments, two at NBS and one at another laboratory. These variabilities, for these sets of data, represented by the average standard deviation σ for several samples of each nominal color, are listed in Table XIV.

4.3 Comparison of Nighttime and Daytime Colors

It would be convenient if the daytime and nighttime chromaticity requirements of the color of a retroreflective material could be specified by using the same chromaticity boundaries. This, of course, can not apply to these materials. In daytime use they are illuminated diffusely with daylight (source D_{65} spectral distribution. In nighttime they are illuminated nearly perpendicularly with light of tungsten filament lamps of color temperature 2856K (source A).

Table XV shows a comparison of the chromaticity coordinates of nighttime and daytime color of retroreflective materials in the NBS set. From these data it can be seen that in daytime the color of the red, orange and yellow retro-reflectors appears weaker than in nighttime while the color of white, green, and blue retroreflectors appears bluer than in nighttime.

Table XIII. Summary of Photometric-Correction Factor for C.I.L./A* Measurements for Several Colors

Color	Gamma Instrument	Pritchard Instrument
Red	0.892	0.917
Yellow Orange	.944	.891
Green	.999	.940
Blue	.882	.691
White	.983	.974

* See paragraph 4.2

Table XIV. Variability of C.I.L./A* in Terms of Average Standard Deviation $\bar{\sigma}$, and Coefficient of Variation V(%)

Retroreflector Color	3 Instruments 2 Laboratories		2 Instruments 1 Laboratory		1 Instrument 2 Readings	
	$\bar{\sigma}$	V(%)	$\bar{\sigma}$	V(%)	$\bar{\sigma}$	V(%)
White	3.4	2.7	2.7	2.1	0.6	0.5
Yellow	1.8	2.4	1.6	2.1	.5	0.7
Red	1.3	6.4	0.6	2.8	.1	0.5
Blue	1.0	11.4	1.2	13.7	.1	1.1
Green	1.4	7.4	1.5	7.9	.1	0.5
Orange	1.4	3.7	0.8	2.1	.5	1.3
All Colors	1.7	5.7	1.7	5.1	0.3	0.8

* See paragraph 4.2.2

Table XV. Comparison of Nighttime and Daytime Color of Retroreflectors

Mfgr's Identity †	No.	Mfgr's Color Name	Source A 5/0.33		Source C 45/0*		Source D_{65} D/0		Source C D/0	
			x	y	x	y	x	y	x	y
S	3302	Red	-	-	0.654	0.324	0.626	0.314	0.625	0.311
S	3282	Ruby Red	0.652	0.346	.654	.318	.622	.324	.621	.322
S	3272	Red	.635	.361	.614	.335	.594	.342	.593	.339
A	238D	Red	.617	.374	-	-	.617	.337	.616	.335
S	3872	Red	.660	.339	.639	.331	.624	.321	.622	.329
M	12A-R	Red	.671	.329	-	-	.575	.329	.573	.326
M	12A-A	Amber	.592	.408	-	-	.542	.410	.541	.408
S	3279	Brown	.621	.373	.489	.379	.482	.384	.481	.377
S	3884	Orange	.607	.384	.552	.395	.548	.399	.547	.397
S	3284	Orange	.549	.400	.569	.386	.547	.390	.546	.387
A	240E	Orange	.596	.378	-	-	.564	.398	.562	.397
S	FEA588	Orange	.592	.405	.572	.389	.565	.395	.565	.393
S	3871	Yellow	.540	.459	.528	.467	.522	.459	.523	.457
S	3271	Yellow	.532	.460	.499	.474	.490	.474	.491	.470
S	FEA675	Yellow	.534	.451	.495	.464	.487	.465	.489	.462
A	242C	Yellow	.533	.441	-	-	.485	.473	.487	.470
S	RF151	Yellow	.439	.423	.437	.464	.415	.457	.417	.449
S	3273	Gold	.488	.434	.435	.415	.429	.421	.429	.414
S	3281	Lemon Yellow	.519	.470	.443	.519	.445	.503	.449	.497
S	3877	Green	.171	.525	.154	.430	.168	.435	.168	.417
S	3277	Green	.204	.586	.126	.414	.156	.440	.157	.422
A	Green	Green	.188	.595	-	-	.140	.454	.141	.436
M	PMO-M	Green	.272	.474	-	-	.213	.346	.213	.330
M	PMO-M/B	Green	.236	.416	-	-	.210	.344	.209	.329

* Date submitted by manufacturer
† S, 3 M Scotchlite; A, American Decal; M, Amerace Stimsonite

Table XV. (Continued)

Mfgr's Identity † No.	Mfgr's Color Name	Source A 5/0.33		Source C 45/0*		Source D_{65} D/0		Source C D/0	
		x	y	x	y	x	y	x	y
S 3276	Gray Blue	0.126	0.324	0.277	0.286	0.218	0.258	0.216	0.244
S 3275	Blue	.106	.228	.145	.115	.156	.143	.155	.135
S FEA681	Blue	.095	.308	.136	.152	.146	.155	.147	.143
S R 150	White	.444	.428	.326	.319	.315	.333	.312	.320
S 3300	White	-	-	.308	.314	.309	.327	.307	.314
A 229E	White	.429	.422	-	-	.314	.336	.311	.322
S 3870	Silver	.395	.410	.303	.310	.301	.320	.299	.307
M 2400	Crystal	.412	.406	-	-	.304	.322	.301	.309
M FOS975	Crystal	.420	.409	-	-	.306	.323	.303	.310
S 3280	Imperial White	.400	.408	.319	.342	.322	.351	.320	.339
S FEA556	Silver	.412	.425	.333	.356	.326	.357	.324	.345
S 3070	Silver	.401	.425	.327	.347	.328	.358	.326	.346
S 3270	Silver	.426	.434	.328	.355	.329	.361	.327	.349
S 3285	Black	.450	.441	-	-	.316	.335	.313	.322

* Data submitted by manufacturer

† S, 3 M Scotchlite; A, American Decal; M, Amerace Stimsonite

5. Recommended Test Procedure for Nighttime Conditions

On the basis of this study the following procedure is recommended for instrumental color measurement of retroreflective materials under nighttime illuminating conditions.

5.1 Colorimeter and Calibration Equipment

The colorimetric equipment shall consist of a source with its power supply, a telecolorimeter with its power supply, and meter, supports or holders for the source, colorimeter, and test samples. Calibration equipment shall consist of calibrated filters and a calibrated reflecting surface, such as MgO, $BaSO_4$ or $MgCO_3$. The equipment shall be placed in a room that is at least 100 feet long and can be darkened as needed.

5.1.1 Source. The source shall be a projector with a tungsten filament lamp and a lens having maximum diameter of two inches. The lamp shall be operated at a voltage to yield a color temperature of the projected light of 2856K. To maintain the lamp voltage the source power supply shall be equipped with voltage regulating equipment that controls voltage to within 0.1 volt.

5.1.2 Telecolorimeter. The telecolorimeter shall be equipped with tristimulus filters and electrical trimming of the output of the photodetector in combination with each of the filters so that tristimulus values have proper relative values. The colorimeter shall have means of focussing the test sample image on the field stop. The field stop shall be of such a size that the field of view is 6 minutes. The telecolorimeter shall have its own power supply, amplifier and output meter. To achieve high accuracy the correction in chromaticity coordinates of test samples resulting from multiplication of the tristimulus value readings by the color-correction factors shall be within ± 0.015 in x and in y, the linearity of the scales shall be within ± 0.010 over the range of 100 to 0.01 and the stability shall be within ± 0.002 in any range.

5.1.3 Supports. There shall be suitable tripods or other supports for the source, telecolorimeter, and samples and means for rotation of the samples as required so that the geometric arrangement required for calibration and measurement can be made. These arrangements are shown in Figures 8 and 9, respectively.

5.1.4 Calibration Standards. Suitable filters, those with relative spectral transmittance curves similar in shape to those of the spectral reflectance of the test samples shall be used. By similar shapes is meant that the ratio of the spectral reflectance of the sample to the spectral transmittance of the filter is approximately constant. If no such filters are available, then the NBS reference filters (item 4.10 of the NBS Std. Ref. Materials catalog) may be used. Standard reflecting materials, 4-inch square plaque of MgO, $MgCO_3$, of $BaSo_4$ may be used as a white standard for calibration.

5.2 Calibration

5.2.1 Arrangement of Equipment. To provide a spectrally non-selective surface, place a white standard plaque in the sample position. Arrange the source, operating at 2856K, the white standard and the telecolorimeter as shown in Figure 10. At a viewing distance of 100 feet and with a 6 minute field stop in place, focus the telecolorimeter upon the center of the white standard plaque. (At 100 feet a 6' field stop limits the field of view of the photometer to approximately a 2-inch circle, thereby permitting use of 4-inch square plaques.)

5.2.2 Adjustments of Meter. Follow the directions in the manufacturer's instruction manual for the telecolorimeter, and adjust the zero settings and sensitivity so that the instrument is calibrated to read luminance. Remove the photopic correction filter before the photoreceptor of the telecolorimeter and replace it with the Y-tristimulus filter. Adjust the distance between the source and the white plaque to obtain a reading of approximately 100 on the meter dial. Next, with each tristimulus filter, positioned in turn before the photoreceptor, adjust the meter instrument so that the meter indicates the correct values for the white plaque. For MgO these are:

$X_r' = 104.45$ $\quad Y' = 100.00$

$X_b' = 5.38$ $\quad Z' = 35.55$

where
where,

X_r' is the reading with filter for the long-wave portion of the X-function,

X_b' is the reading with filter for the short-wave portion of the X-function,

Y' is the reading with the filter for the spectral luminance efficiency function, and

Z' is the reading with the filter for the Z-function.

5.2.3 Reference Filters. With the telecolorimeter focussed on the illuminated white plaque, insert each of the standard filters in turn into the auxiliary filter slot as needed, read, and record the tristimulus values, X_r', X_b', Y' and Z'.

5.2.4 Color-Correction Factors. From the data obtained with the standard filters and the white standard, calculate the correction factors, F_X, F_Y and F_Z for the tristimulus values of each of the standard filters by means of the following equations.

$$F_X = X/(X'_r + X'_b)$$

$$F_Y = Y/Y'$$

$$F_Z = Z/Z',$$

where X, Y, and Z are the correct tristimulus values of the standard filters.

The magnitude of the correction factors for the tristimulus values are indications of the closeness of the fit to the CIE functions. To ascertain that the instrument's filters fit, limits should be set on the size of the correction factors. We suggest that the correction factors lie between 0.8 and 1.2, except that for red retroreflectors the F_Z factor may be no less than 0.2. (The instruments used in this investigation did not meet these requirements.)

5.3 Color Measurement Procedure

5.3.1 Arrangement of Equipment. Reposition the source telecolorimeter, and sample holder to achieve the arrangement of components shown in Figure 9. Make no changes in the adjustments of the telecolorimeter. To minimize errors that may result from variations of source color temperature from 2856K, use the same light source in the color measurement as was used in the calibration.

5.3.2 Colorimetric Observations and Computations. Read the tristimulus values of the samples, X_r', X_b', and Z', to three significant figures. Record these as simple readings. Correct the tristimulus values of the sample colors by the use of the following equations:

$$X = [X'_r + X'_b]\ F_X$$

$$Y = Y'\ F_Y$$

$$Z = Z'\ F_Z,$$

where F_X, F_Y and F_Z are the color-correction factors obtained in the calibration above for the reference filter with spectral characteristics similar to those of the test samples. Compute the CIE chromaticity coordinates x, y of the test sample color by the use of the following equations:

$$x = X/(X + Y + Z)$$

$$y = Y/(X + Y + Z)$$

5.4 Photometric Measurement Procedure

5.4.1 Photometer Specification. Because a large variety of photometric instruments may be used, including a telephotometer, it is essential that the instrument actually used be described. The entrance and observation angles must be specified and test geometry defined either by angular apertures of source, receptor, and sample or by their dimensions together with the test distance. Further, specify the position angle if different from 0°, and specify the rotation angle if sample characteristics are orientation dependant.

The photometric equipment shall consist of the same components as described in 5.1 for the colorimetric equipment. The receiver shall be either color corrected or color-correction factors for the Y tristimulus value be known and applied. The linearity of photometric scale shall be within ± 0.010 over a range of values from 100 to 0.01. The instrumental stability shall be within ±0.002 in any range.

5.4.2 Specific Intensity per Unit Area. Set the specified distance from the test sample surface to the source and to the photometer. (See 5.4.3). Measure the illuminance of the face of the reflector by substituting a receptor for the retroreflector, with its entrance window at the place where the face of the retroreflector will be mounted. If a telephotometer is used, choose the smallest field stop which is large enough to include the entire image of the source. Record reading as R_1. Put the retroreflector in place. Orient it so that the desired entrance and orientation angles are obtained. (See Figure 9). Place the receptor at a lateral distance, d, from the source so that

$\tan^{-1} d/D = \alpha$

where α is the desired observation angle. See Figure 9. If a telephotometer is used choose the smallest field stop which is large enough to include the entire image of the retroreflector inside the field stop.

Determine its luminous intensity by measuring the illuminance at the receptor in the same units as R_1 (reading R_2). The coefficient of the luminous intensity (C.I.L.), or in the United States usage the specific intensity (S.I.), may then be computed from the relation

$$\text{C.I.L. or S.I.} = R_2(D')^2/R_1$$

where D' is the distance between the retroreflector and the receptor. When colored samples are measured it is usually desirable to correct for the deficiencies in the Y filter of the photometer by means of a filter having a spectral transmittance approximating that of the retroreflector. Obtain calibration factor K by the formula

$$K = R_1 T/R_F,$$

where

- R_1 is illuminance of the face of the retroreflector determined as described above,
- R_F is the reading of the receptor at the same position as for R_1 but with a color filter placed immediately in front of the receptor, and
- T is known (total) luminous transmittance of the filter.

The corrected specific intensity of the retroreflector is then

$$\text{C.I.L. or S.I.} = K\, R_2(D')^2/R_1 = R_2(D')^2\ T\ R_F$$

Note that this method is applicable only when the same receptor is used to measure both the normal illuminance at the retroreflector, E_n and the normal illuminance produced by the retroreflector at the receptor, E'_n. If different receptors are used for these measurements, then the color-correction factor of the receptor used to measure E'_n must be determined by a separate set of measurements. Note that if the same photometer is used for the determination of R, (and R_F) and R_2, calibration of the photometer is not required if the instrument is sufficiently linear. If separate photometers are used,

or if the instrument is not sufficiently linear, each (range used) shall be calibrated by using a standard lamp.

Because of the wide variety of photometric instruments, a complete description of the calibration procedure for all types of instruments would be too lengthy for this document. Accordingly, it is recommended that users follow the usual procedure given by the manufacturer unless required to do otherwise in special applications.

Since, by definition, specific luminance (S.L.) is the specific intensity (S.I.) per unit projected area,

$$S.L. = S.I./A \cos \varepsilon_2 \text{ or}$$

$$S.L. = KR_2D^2/R_1 \; A \cos \varepsilon_2$$

where

A is the effective retroreflector surface area and

ε_2 is the entrance angle.

Specific intensity per unit area (C.I.A. or S.I.A.) is given by

$$C.I.A. = C.I.L./A = K \; R_2(D')^2/R_1A$$

where the meter is the unit of length, or

$$S.I.A. = S.I./A = KR_2(D')^2/R_1A,$$

where the foot is the unit of length.

A luminance meter is often used as the receptor in the evaluation of retroreflecting sheet instead of an illuminance meter. When a luminance meter is used care must be taken to insure that the image of the retroreflector completely fills the field stop of the luminance meter. The photometric procedures are essentially unchanged except that the color-correction factor of the luminance meter k must be obtained separately and the following relations apply:

$$S.L. = kR_L/R_1 \cos \varepsilon_2$$

and

$$S.I.A. = kR_L/R_1$$

where

R_L is the reading of the luminance meter in candelas per unit area.

5.4.3 Special Precautions. For cube-corner reflectors in vehicular and highway use, the suggested measurement geometry is reflector-receptor distance 30 meters (100 feet), receptor diameter 1.25 cms (0.5 inch) and source diameter 5 cms (2 inches). Such equipment is also suitable for a material such as beaded sheet that has a relatively flat curve of specific intensity versus observation angles, but for cost reasons the laboratory testing only beaded sheet may prefer a reflector-receptor distance of 15 meters (50 feet), receptor size of 2.5 cms (1 inch) and a source size of 2.5 cms (1 inch). This geometry is adequately precise for beaded sheet but not for the cube-corner reflector. Much longer distances are needed for the very precise cube-corner reflectors.

Care should be exercised to minimize the effects of stray light. The background of the retroreflector should be flat black. The field of view of the receptor should be made as small as feasible. Baffles should be used where appropriate to limit the spread of the source. By the use of a black surface of the same shape and area as the test sample a measurement of the amount of stray light can be made. The stray-light reading so obtained should be subtracted from the reading R_2, obtained with the retroreflector in place.

When measurements are being made of the output of colored retroreflectors it is essential that the source have the specified color temperature, or spectral distribution. Because the intensity, as well as the spectral distribution, of a light source varies with the applied voltage, care should be taken to assure that the voltage be stable. To stabilize the intensity of the light source to within 1% the voltage should be stabilized to within 0.3%.

In reporting data for retroreflectors, conditions of measurement -- observation angle, entrance angle, viewing angle, and rotation angle -- should always be reported. Accordingly, the geometry of the measurement equipment should be specified either by reference to a standard (such as SAE J 594 or LS-300) or by itemizing source size, receptor size and retroreflector-receptor distance.

6. Recommended Color Specifications of Retroreflective Materials

The Interim Report on Recommendations for Surface Colors for Visual Signalling by the Subcommittee on Surface Colors of the CIE Committee TC 1.6, Fundamentals of Light Signals and Signs contains the following comment on the nighttime appearance of retroreflective (sheet) materials:

"Night-time appearance. This document makes no specific recommendations for the measurement of the colours of retro-reflective materials with the special geometries that are typical of the illuminating and viewing conditions at night-time. The reasons for the omission of definite advice are related to the current technical difficulties of making measurements on retro-reflective materials at small observation angles, and the present lack of reproducibility of results between different colorimetric laboratories. Consequently, the night-time appearance of the colours of retro-reflective materials should be assessed by visual inspection with the illuminants likely to be used, and the illuminating and viewing geometries likely to occur."

Elsewhere in the subcommittee's report the following comment is made about all material surfaces with the color brown:

"Brown. This document makes no specific recommendation with regard to any color commonly called brown."

Because brown cannot be distinguished from yellow or orange, if luminances can not be compared, its color will not be specified.

In this report, tentative recommendations will, nevertheless be made for specification of the colors of retroreflective materials, excluding the color brown, for nighttime conditions, based on the results obtained in this study. These specifications are based only upon available chromaticity characteristics and not upon visual aspects of the problem.

Because colors under nighttime conditions differ from the colors under daytime conditions, different sets of specifications are required. Present daytime color specifications are also included for comparison.

The color specification requirements for retroreflective materials such as delineators and lane markers which are viewed as point sources are different from those for retroreflective sheet materials viewed as surfaces. These two types will be treated separately. The color boundaries are described by equations. When, however, it is desired to plot the chromaticity regions on a chromaticity diagram, it is often easier and quicker to do this by joining by straight lines points corresponding to the intersections of the boundaries than by drawing the boundaries from their specifying equations. The coordinates of these points are therefore given.

6.1 Color Specifications for Retroreflective Delineators and Lane Markers at Nighttime

For retroreflectors of small size which appear as point, or near-point, sources color boundaries recommended by the International Commission on Illumination (CIE) should be used. Because these markers are used by drivers with color deficient vision as well as normal, restricted boundaries of the CIE signal light colors have been selected for this purpose. The equations for the boundaries selected and intersection points are listed in Table XVI. The boundaries are plotted on Figure 21.

For red color specifications, the restricted boundaries for persons who are red-green confusers were recommended.

The use of the color orange in delineators and lane markers is not recommended because orange sources of small angular subtense will be confused with red and yellow.

For yellow, the restricted white boundary recommended to obtain greater discrimination from white was chosen.

For green, the restricted yellow boundary recommended for persons who are red-green confusers and the restricted blue boundary to obtain greater discrimination from blue was chosen.

For white, the coded white boundary recommended to obtain greater discrimination from yellow was chosen.

6.2 Color Recommendations for Retroreflective Sheet Materials at Nighttime

6.2.1 NBS Recommendations for Nighttime Color Specifications

Color specifications of retroreflective sheet under night conditions are tentatively recommended. The boundaries for each color have been chosen to include as large an area as practicable and to be consistent with the data obtained in this study. The option of supporting any CIE recommendations if and when they are formulated and receive international acceptance at some time however, is reserved.

The specifications for the coefficients of luminous intensity, C.I.L./A, and color recommended for retroreflective sheeting materials in nighttime conditions under 5/0.33 geometry are listed in Table XVII. The

Table XVI. NBS Recommended Color Specifications for Retroreflective Delineators and Lane Markers at Nighttime

Color	Boundary	Boundary Equation	Chromaticity Coordinates of the Boundary Line Intersection Points							
			x	y	x	y	x	y	x	y
Red	Red	$y = 0.290$	0.710	0.290	0.700	0.290	0.655	0.335	0.665	0.335
	White	$y = 0.990 - x$								
	Yellow	$y = 0.335$								
Yellow	Red	$y = 0.382$	0.618	0.382	0.612	0.382	0.555	0.435	0.560	0.440
	White	$y = 0.951 - 0.930x$								
	Green	$y = x - 0.120$								
Green	Yellow	$y = 0.726 - 0.726x$	0.321	0.493	0.245	0.377	0.013	0.494	0.009	0.720
	White	$x = 0.650y$								
	Blue	$y = 0.500 - 0.500x$								
Blue	Green	$y = 0.065 + 0.805x$	0.233	0.167	0.148	0.025	0.090	0.137	0.186	0.214
	White	$y = 0.400 - x$								
	Violet	$x = 0.133 + 0.600y$								
White	Yellow	$x = 0.500$	0.500	0.382	0.440	0.382	0.285	0.264	0.285	0.332
	Red	$y = 0.382$								
	Purple	$y = 0.047 + 0.726x$			0.453	0.440	0.500	0.440		
	Blue	$x = 0.285$								
	Green	$y = 0.150 + 0.640x$								
		$y = 0.440$								

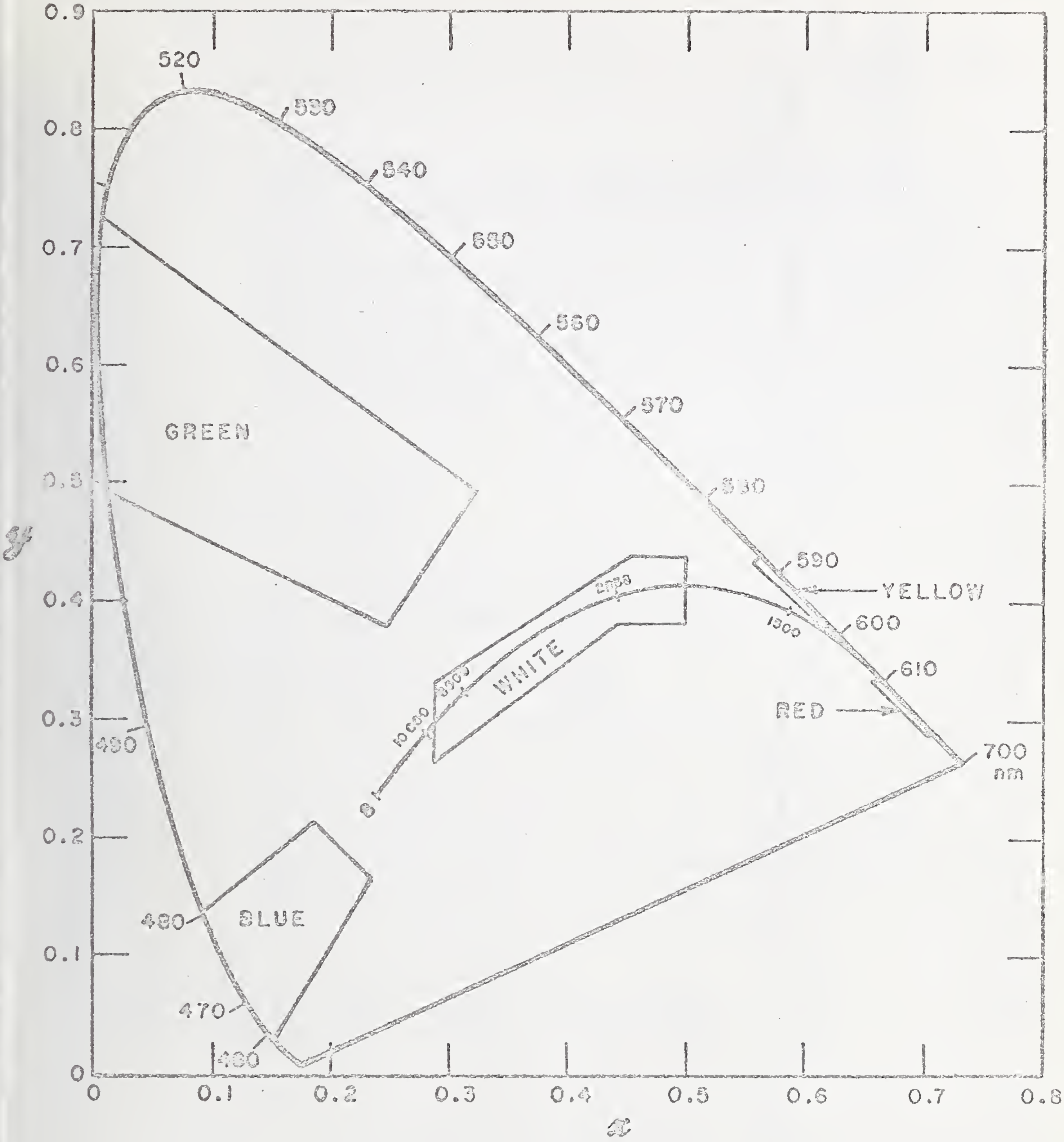


Figure 21. Recommended color boundaries for retroreflective delineators and lane markers at nighttime.

Table XVII. NBS Recommended Color and C.I.L./A* Specifications of Retro-reflective Sheet Materials at Nighttime

Color Name	Boundary	Boundary-Line Equation	C.I.L./A Range* (5/0.33) Low	High
Red	Red	$y = 0.300$	15	45
	White	$y = 0.980 - x$		
	Orange	$y = 0.350$		
Orange	Red	$y = 0.350$	20	70
	White	$y = 0.950 - x$		
	Yellow	$y = 0.400$		
Yellow	Orange	$y = 0.400$	25	145
	White	$y = 0.980 - x$		
	Green	$y = 0.460$		
Green	Yellow	$x = 0.372 - 0.155y$	8	40
	White	$y = 0.286x + 0.447$		
	Blue	$x = 0.527 - 0.684y$		
Blue	Green	$y = 0.500x + 0.250$	4	25
	White	$x = 0.150$		
	Purple	$y = 0.772x + 0.077$		
Silver (White)	Purple	$y = 0.250x + 0.275$	50	225
	Yellow	$x = 0.500$		
	Green	$y = 0.500x + 0.225$		
	Blue	$x = 0.400$		

* See Tables XI and XII

boundary lines for these colors are shown in Figure 22. (The boundary lines are also shown on Figures 15 to 20.) In Table XVIII are listed the x, y chromaticity coordinates to aid in plotting the boundary lines.

6.2.2 Recommendations by 3M Company for Nighttime Color Specifications. The 3M Company has also made recomendations for nighttime color specifications of retroreflective sheeting materials. These regions specified are considerably broader than the NBS recommendations. For comparison the 3M recommendations are given in Table XIX, together with the x, y chromaticity coordinates of the intersection points of the boundary lines. The boundaries are also shown on Figure 23. The following will be noted from this figure:

1. Orange over-laps red on one side and yellow on the other.

2. White is too close to yellow.

3. Blue extends into the region of the diagram usually described as green.

6.3 Present Daytime Color Specifications

To complete the specification description and to serve as a convenient comparison, present daytime color and luminance factor specifications are included. These are the standard highway sign color and luminance factor specifications for daytime, listed in FHWA Data Sheet TO-21, September, 1971, and the NJCUTCD boundaries for surface colors, which are given in Table XX. The boundaries have been plotted on Figure 24.

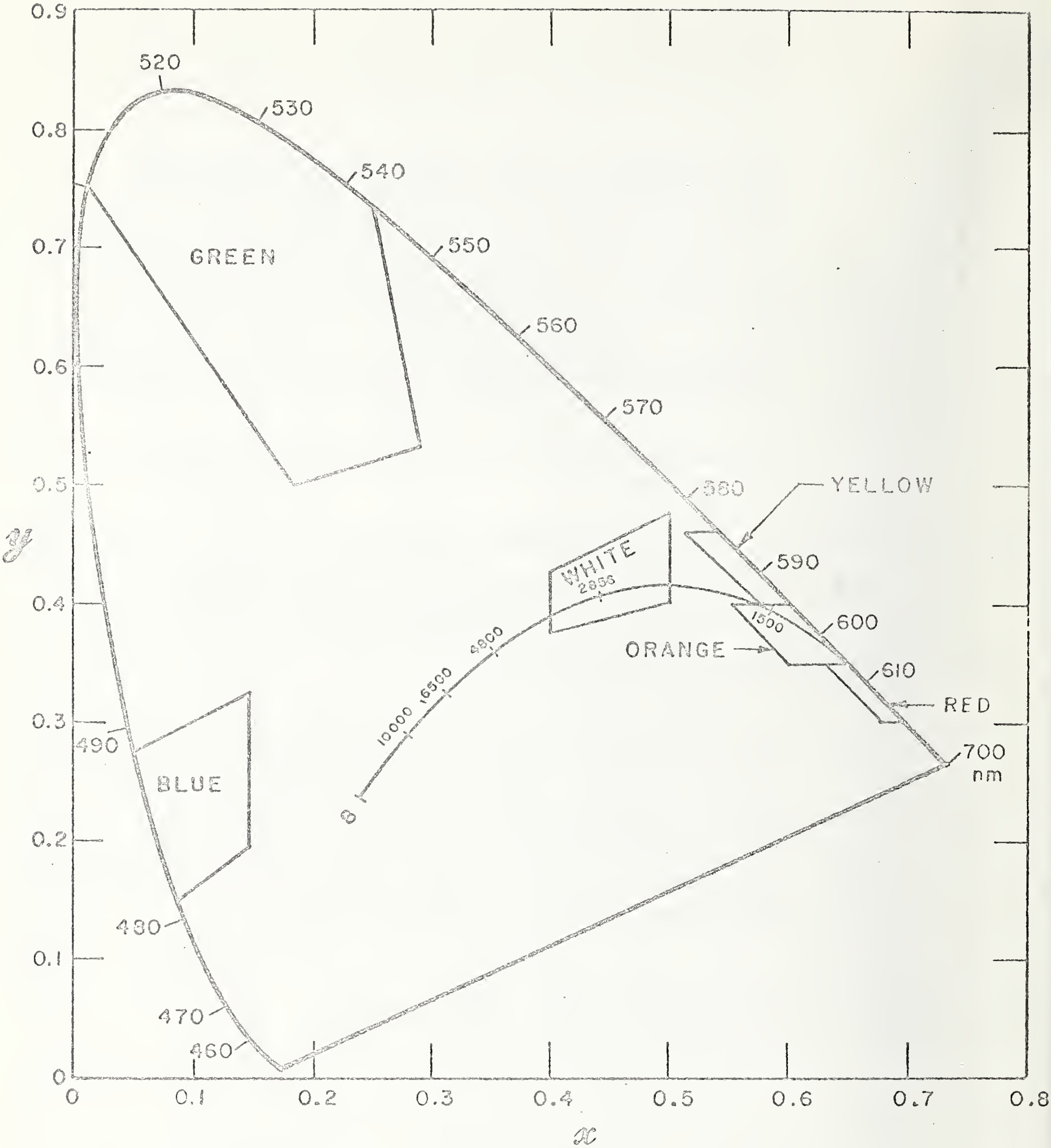


Figure 22. NBS recommendations for color specifications of retroreflective sheet materials at nighttime.

Table XVIII. Chromaticity Coordinates of Intersections of NBS Recommended Boundary Lines for Retroreflective Sheet Materials at Nighttime

Color	Chromaticity Coordinates of the Boundary Line Intersection Points							
	x	y	x	y	x	y	x	y
Red	0.630	0.350	0.680	0.300	0.700	0.300	0.650	0.350
Orange	.550	.400	.600	.350	.650	.350	.600	.400
Yellow	.520	.460	.580	.400	.600	.400	.540	.460
Green	.014	.750	.185	.500	.290	.530	.259	.730
Blue	.050	.275	.087	.144	.150	.193	.150	.325
Silver (White)	.400	.425	.400	.375	.500	.400	.500	.475

Table XIX. 3 M Recommended Specifications for Retroreflective Sheet Materials at Nighttime

Color Name	Boundary	Boundary Line Equation	Intersection Points x	Intersection Points y	x	y	x	y	x	y
Red	Red	$y = 0.324 - 0.037x$	0.582	0.365	0.648	0.300	0.702	0.298	0.627	0.373
	White	$y = 0.939 - 0.986x$								
	Orange	$y = 0.178x + 0.261$								
Orange	Red	$y = 0.143x + 0.246$	0.530	0.395	0.590	0.330	0.660	0.340	0.580	0.420
	White	$x = 0.895 - 0.923y$								
	Yellow	$y = 0.500x + 0.130$								
Yellow	Orange	$y = 0.318x + 0.199$	0.503	0.467	0.586	0.385	0.608	0.391	0.520	0.480
	White	$x = 0.964 - 0.988y$								
	Green	$y = 0.812x + 0.058$								
Green	Yellow	$x = 0.372 - 0.155y$	0.014	0.750	0.185	0.500	0.290	0.530	0.259	0.730
	White	$y = 0.286x + 0.447$								
	Blue	$x = 0.527 - 0.684y$								
Blue	Green	$y = 0.450$	0.087	0.144	0.210	0.239	0.200	0.450	0.018	0.450
	White	$x = 0.221 - 0.047y$								
	Purple	$y = 0.772x - 0.077$								
Silver (White)	Purple	$y = 0.420x + 0.184$	0.372	0.403	0.417	0.359	0.548	0.414	0.450	0.513
	Yellow	$y = 0.958 - 0.990x$								
	Green	$x - 0.964y + 0.086$								
	Blue	$y = 0.766 - 0.978x$								

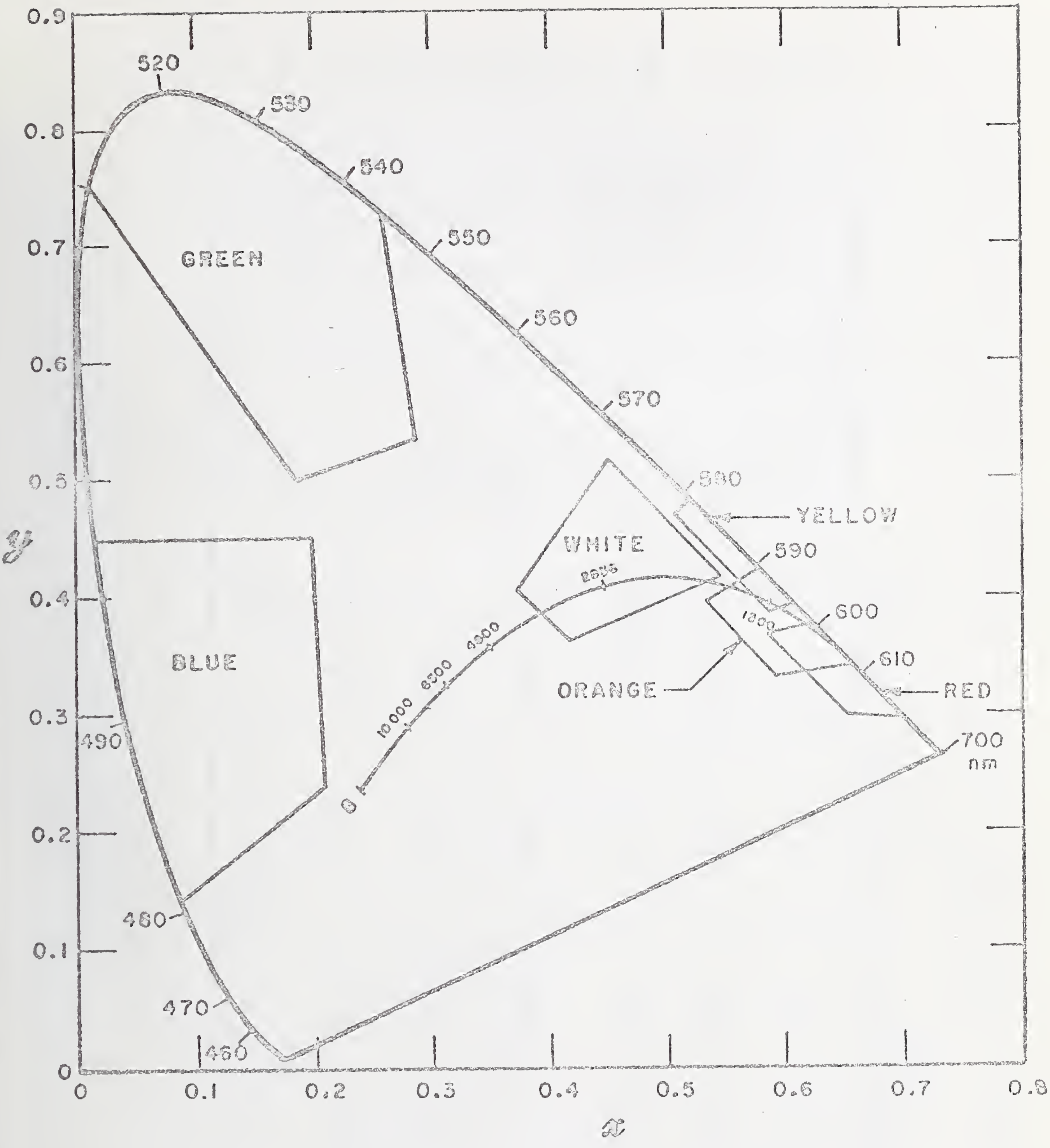


Figure 23. Recommendations of the 3M Company for color specifications of retroreflective sheet materials at nighttime.

Table XX. Present Color and Luminance Factor Specifications for Retroreflective Sheet Materials in Daytime

Color Name	Central* Chromaticity x	Central* Chromaticity y	Luminance Factor* Range Low	Luminance Factor* Range High	Boundary†	Boundary-Line Equations†
Red	0.600	.315	6.56	12.00	Purple	$y = 0.602 - 0.500x$
					White	$x = 0.500y + 0.424$
					Orange	$y = 0.442 - 0.200x$
Orange	.561	.395	19.77	30.05	Red	$y = 0.236 - 0.259x$
					White	$x = 0.535$
					Yellow	$y = 0.202 + 0.368x$
Brown	.477	.382	3.81	7.71	Red	$y = 0.232 + 0.273x$
					White	$x = 0.445$
					Yellow	$y = 0.156 + 0.518x$
Yellow	.501	.456	36.20	59.10	Orange	$y = 0.114 + 0.653x$
					White	$x = 0.705 - 0.500y$
					Green	$y = 0.053 + 0.848x$
Green	.209	.410	3.82	10.43	Yellow	$y = 0.748 - 1.394x$
					White	$y = 1.732x - 0.016$
					Blue	$y = 0.481 - 0.532x$
Blue	.178	.183	3.13	9.00	Green	$y = 0.872x + 0.046$
					White	$y = 0.412 - x$
					Purple	$y = 1.143x - 0.038$
Silver† (White)	.306	.316	None Given		(NG)	

* After Federal Highway Administration Color Tolerance Charts, 1971

† NJCUTCD Specifications for Surface Colors

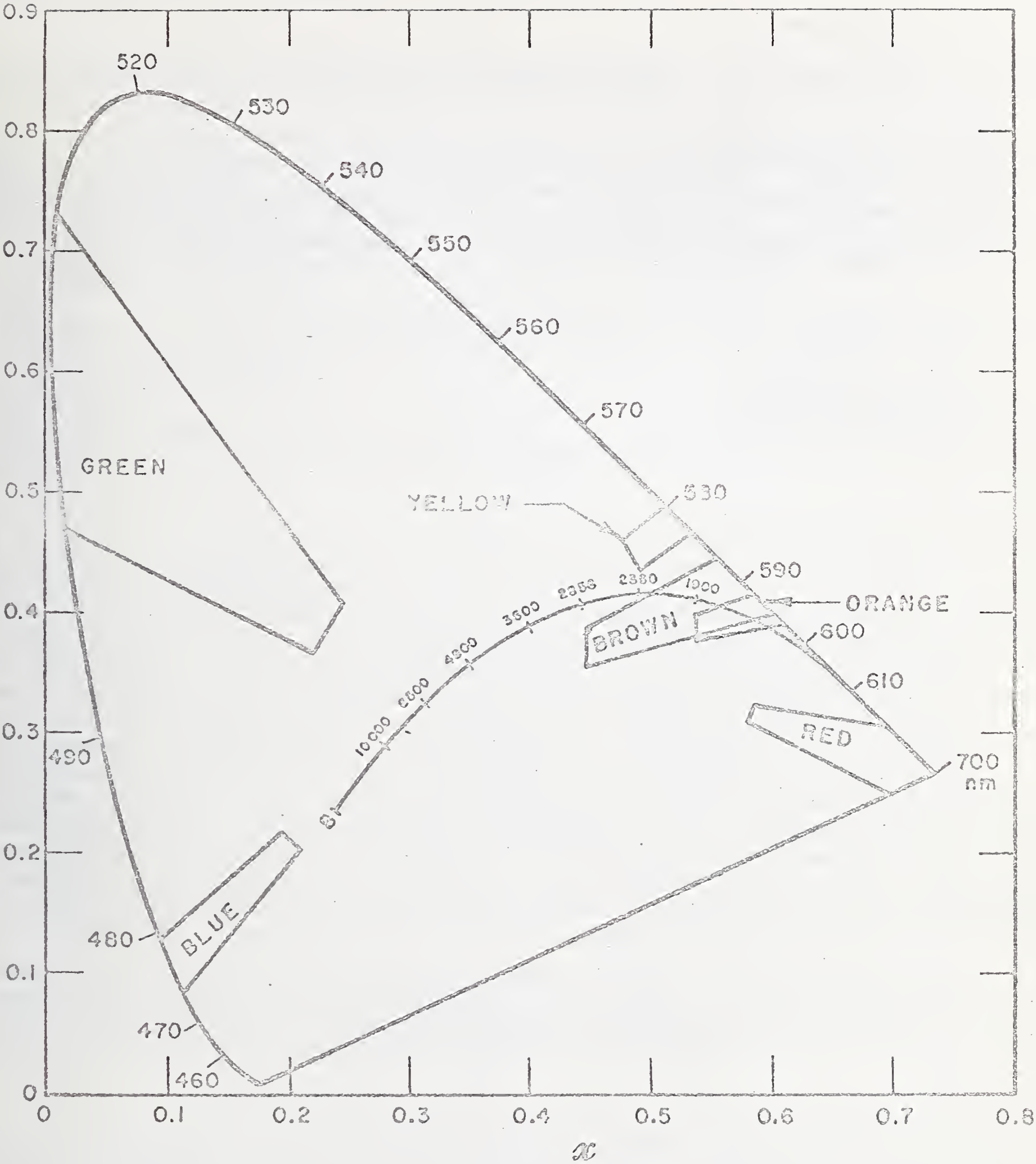


Figure 24. Present surface color boundaries of the NJCUTCD for daytime.

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15. SUPPLEMENTARY NOTES

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

Because color-coded applications of highway signs increase, specifications of colors and color tolerances are required. In order to assure that the requirements are met within specified regions, a measurement technique needs to be developed and described. To accomplish these goals the U. S. Department of Transportation contracted with the National Bureau of Standards to conduct the required studies and make the necessary recommendations. Having previously performed a study for daytime conditions, the National Bureau of Standards was competent to perform a study for nighttime conditions. The colorimetric properties of 126 samples of retroreflective materials of 7 different colors were measured with 3 telecolorimeters in simulated nighttime conditions. One spectrophotometer was used to measure color of 38 of the samples in simulated daytime conditions. The colors measured were: red, orange, brown, yellow, green, blue and silver (white). Differences of color measured by means of different telecolorimeters on the same samples were evaluated.

As a result of these studies procedures for making colorimetric and photometric measurements were developed and are included in this report. On the basis of the color measurements and their variability tentative recommendations for color boundaries were prepared and are also included in this report.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Colorimetry; highway signs; photoelectric tristimus colorimeters; photometry of retroreflective materials; retroreflective sign materials

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